

# VARIATIONS IN WATER STORAGE CAPACITY OF A MOUNTAIN PEATLAND WITH COMPLEX STRATIGRAPHY

A thesis Submitted to the  
College of Graduate and Postdoctoral Studies  
In Partial Fulfillment of the Requirements  
For the Degree of Master of Science  
In the Department of Geography and Planning  
University of Saskatchewan  
Saskatoon

By  
Selena Rae Schut

© Copyright Selena Rae Schut, September 2021. All rights reserved.  
Unless otherwise noted, the copyright of the material in this thesis belongs to the author.

## **PERMISSION TO USE**

In presenting this thesis/dissertation in partial fulfillment of the requirements for a Master of Science degree from the University of Saskatchewan, I agree that the Libraries of this University may make it freely available for inspection. I further agree that permission for copying of this thesis in any manner, in whole or in part, for scholarly purposes may be granted by the professor or professors who supervised my thesis work or, in their absence, by the Head of the Department or the Dean of the College in which my thesis work was done. It is understood that any copying or publication or use of this thesis or parts thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to me and to the University of Saskatchewan in any scholarly use which may be made of any material in my thesis.

## **DISCLAIMER**

Reference in this thesis/dissertation to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement, recommendation, or favouring by the University of Saskatchewan. The views and opinions of the author expressed herein do not state or reflect those of the University of Saskatchewan and shall not be used for advertising or product endorsement purposes.

Requests for permission to copy or to make other uses of materials in this thesis/dissertation in whole or part should be addressed to:

Head of the Department of Geography and Planning  
Department of Geography and Planning  
117 Science Place  
University of Saskatchewan  
Saskatoon, Saskatchewan, S7N 5C8  
Canada

OR

Dean  
College of Graduate and Postdoctoral Studies  
University of Saskatchewan  
116 Thorvaldson Building, 110 Science Place  
Saskatoon, Saskatchewan, S7N 5C9 Canada

## **ABSTRACT**

Peatlands in the Rocky Mountains most commonly occur in valley bottoms and are classified as fens. Understanding how fens influence water storage and water release is essential for better predicting water availability as the climate changes. Peatlands located in mountain regions tend to have a complex soil profile due to the geomorphologically dynamic environment. There is little information on the water storage capacity of mountain peatlands. To address this knowledge gap, the water storage capacity of a fen peatland with a complex soil profile in the Canadian Rocky Mountains, Alberta, Canada, was studied. Using the water table fluctuation method, vertical variations in specific yield were estimated. The influence of several factors – soil profile complexity, vegetation cover, water table depth, and seasonality – on specific yield were determined. Results showed that soil profile complexity plays a vital role in determining the spatial variability of vertical specific yield. The effect of stratigraphy on specific is important because it demonstrates that active geomorphic environments (often found in mountain regions) are a crucial piece of information required to determine the water storage capacity of mountain fens. The seasonality analysis results show that the overall wetness of a given year or time during the growing season influences the water table depth and response to rainfall events, thus exerting a control on specific yield. The impact of seasonality is also important because it reveals that even small changes to weather patterns can impact water storage in mountain peatlands. Overall, the research yielded new insights into how much water is stored in and released from mountain fens, information which is useful to improving regional hydrological models and predicting hydrological impacts of climate change or geomorphic events.

## **ACKNOWLEDGEMENTS**

First and foremost, I would like to thank my supervisor Dr. Cherie Westbrook for all the support and help she gave me throughout my master's program. I'd like to thank my committee members Jill Blakley and Grant Ferguson for their support and encouragement as well as my external examiner Laura Smith for her help in polishing my thesis. I'd especially like to thank Maria Sanchez, and Tariq Munir for all their help with fieldwork.

Thank you to the Natural Sciences and Engineering Research Council of Canada (NSERC), the NSERC CREATE for Water Security program, the Canada First Research Excellence Fund (Mountain Water Futures), the Canadian Foundation for Innovation, and the Alberta Innovates - Water Innovation Program for their financial support.

A huge thank you to thank my mom and sister for reading the same paragraphs over and over to make sure they were readable and for all their support during my studies. And a massive thanks to my partner for their help in writing and troubleshooting my R scripts throughout the data analysis process.

## Table of Contents

PERMISSION TO USE .....	II
DISCLAIMER .....	III
ABSTRACT .....	IV
ACKNOWLEDGEMENTS .....	V
LIST OF FIGURES .....	VIII
LIST OF TABLES .....	X
LIST OF ABBREVIATIONS .....	XI
1. INTRODUCTION .....	1
2. LITERATURE REVIEW .....	3
2.1 Peatland Overview .....	3
2.1.1 What is a Peatland? .....	3
2.1.2 Ombrotrophic versus Minerotrophic Peatlands .....	3
2.2 Why Peatlands are Important .....	4
2.3 Mountain Peatlands .....	5
2.4 Water Supplies to Peatlands .....	6
2.4.1 General Peatland Hydrology .....	6
2.4.2 Mountain Peatland Hydrology .....	6
2.5 Peatland Sensitivity to Changes in Water Supply due to Climate Change .....	7
2.6 Peatland Water Storage .....	8
2.6.1 Hydraulic Characteristics of Peat .....	9
2.6.2 Estimating Specific Yield from Water Table Records .....	12
2.7 Research Challenge .....	14
3. METHODS .....	15
3.1 Site .....	15
3.2 Data .....	17
3.2.1 Data Collection .....	17
3.2.2 Data Analysis .....	22
4. RESULTS .....	26
5. DISCUSSION .....	43
5.1 Specific Yield and Depth .....	43
5.2 Spatial Specific Yield .....	46

5.3 Temporal Specific Yield .....	47
5.4 Factors Regulating Specific Yield .....	49
6. CONCLUSION .....	51
6.1 Implications.....	51
6.2 Limitations .....	52
6.3 Recommendations .....	53
7. REFERENCES .....	55
APPENDIX A - R Script .....	62
APPENDIX B - Specific yield for Sibbald Fen.....	65
APPENDIX C - Plot of WTD by well .....	66

## LIST OF FIGURES

Figure 2.1 Diagram of soil profile complexity in mountain peatlands using Sibbald Fen, located in the Canadian Rocky Mountains, as an example. Illustration by A. Ronnquist, used with permission. ....	7
Figure 2.2 Visual representation of how to calculate the amount of water lost from storage in a peat column due to a change in the water table. ....	11
Figure 2.3 Diagram depicting how to extract the change in water table following a rainfall event from observations of water table depth (line) and precipitation (bars). ....	13
Figure 3.1 Map of Sibbald fen. Light blue wells indicate the wells studied from within the larger well network shown in dark blue. The meteorological station was relocated in 2017 from the W60A to the W60 B location. ....	16
Figure 3.2 Diagram depicting the variables used to calculate water table depth, $x$ . ....	19
Figure 3.3 Simple diagram displaying the 3 soil profile classes (A) and visualization of soil profiles at each well monitored during the study period (B). Red circles indicate the completion depth of each well. ....	20
Figure 3.4 $S_y$ and water table fluctuation relationship for rainfall events that produced a $S_y > 1$ . ....	23
Figure 3.5 Average air temperature change for dividing the growing season. The orange line indicates 10°C, which was the threshold used to determine average air temperature differences between the three time period categories. ....	24
Figure 3.6 Observed change in vegetation throughout the growing season at Sibbald Fen. A. May-June vegetation, B. July-August vegetation, and C. September vegetation. ....	25
Figure 4.1 SPI graph for 2008 through 2020. ....	26
Figure 4.2 Total number of rainfall events ( $P_i$ ) and number of rainfall events that fit the analysis inclusion criteria laid out in section 4.2.2.1 ( $P_i$ ) occurring between May 1st and October 31st of each studied year. ....	27
Figure 4.3 Density distribution of all 733 rainfall events ( $P_i$ ) considered in this research. ....	28
Figure 4.4 Density distribution plots of rainfall events, $P_i$ (A) and their intensity (B) used in the analysis. ....	28
Figure 4.5 Boxplots of the magnitude (A) and intensity (B) of $P_i$ by month. ....	29
Figure 4.6 Well hydrograph and hyetographs for each year and well during the study period. Gaps in the hydrograph record are periods of no data. ....	32
Figure 4.7 Density distribution of initial water table, $WT_i$ (A) and peak water table, $WT_p$ (B) for the rainfall events used to calculate specific yield. ....	33
Figure 4.8 Density distribution of the magnitude of water table fluctuation for a rainfall event, $\Delta WT_s$ per 10 mm of rainfall. ....	33
Figure 4.9 Boxplots of change in water table ( $\Delta WT_s$ ) per 10 mm of rainfall for each well site studied. ....	34
Figure 4.10 Boxplot of $WT_i$ , $\Delta WT_s$ , and $S_y$ throughout the progression of the growing season. ....	35
Figure 4.11 Boxplot describing the distribution of $WT_i$ (A), $\Delta WT_s$ (B), and $S_y$ (C) values between the years studied. ....	35
Figure 4.12 $\Delta WT_s$ and $S_y$ variation by soil profile. ....	36
Figure 4.13 $\Delta WT_s$ and $S_y$ as a function of % sedge cover class. ....	36



Figure 4.14 Relationship between $S_y$ and $WT_i$ . The dark grey range indicates the 95% confidence interval for the data between 0 and -50 cm depth. ....	37
Figure 4.15 Density distribution of $S_y$ (A) and bootstrapped $S_y$ (B). In B, the red and blue lines represent the lower and upper 95th percentiles, respectively. ....	38
Figure 4.16 Water table variation as a function of rainfall size (points). The red lines and their value indicate $S_y$ .....	38
Figure 4.17 Range of $S_y$ values categorized by well. ....	39
Figure 4.18 Map showing kriged $S_y$ at Sibbald Fen with the fen cropped into a rectangular domain.....	40
Figure 4.19 Visualization of % sedge cover at each well studied at Sibbald Fen. ....	42

## **LIST OF TABLES**

Table 3.1 Well monitoring overview for the study period. ....	16
---	----

## LIST OF ABBREVIATIONS

a	Hanging length of the levellogger within the well
A	Area
$\alpha$	Compressibility of soil
b	Stick-up of the well above the ground surface
$\beta$	Compressibility of water
c	Water level recorded by the levellogger
CI	Confidence interval
dH	Change in hydraulic head
dx	distance
g	Gravity
$K_{sat}$	Saturated hydraulic conductivity
MET	Meteorological
P	Rainfall
$P_t$	Total (733) rainfall events
$P_i$	Included (217) rainfall events
PMP	Peat-mineral-peat
PMG	Peat-mineral-gravel
PP	Purely peat
$\rho_b$	Bulk density
$\rho_m$	Soil particle density
$\rho_w$	Density of water
$\phi$	Porosity
q	Specific discharge
S	Storativity
$S_r$	Specific retention
$S_s$	Specific storage
$S_y$	Specific yield
$\Delta V_w$	Volume of water discharged
V	Volume of soil
$V_r$	Volume of water held by gravity

$V_t$	Bulk volume of soil
$V_{\text{water}}$	Volume of water lost from storage
$V_y$	Volume of water drained by gravity
$\Delta WT$	Change in water table depth
$\Delta WT_s$	Scaled change in water table depth
$WT_i$	Initial water table depth
$WT_p$	Peak water table depth
$WTD$	Water table depth
$WTF$	Water table fluctuation(s)
$x$	Actual water table depth measured from well

## 1. INTRODUCTION

Peatlands are a type of wetland in which organic soil accumulates. Globally, peatlands account for nearly 3% of all land cover – in Canada, they cover approximately 10% of the country's landmass (Xu et al., 2018; Whitfield et al., 2009). Peatlands occur widely in mountain areas, including in the Rocky Mountains (Cooper et al., 2012). Many mountain peatlands rely primarily on groundwater resources to maintain their high water tables and biodiversity, and are thus classified as fens (Winter, 1999; Whitfield et al., 2009).

In mountain regions, peatlands differ from those located elsewhere due to their complex stratigraphy and hydrology (Wang et al., 2016; Morrison et al., 2015). Mountain regions are geomorphologically active, meaning that they are constantly changing by geomorphic processes such as avalanches and river/stream erosion. These processes lead to deposition of mineral sediment deposited in basins and valleys where peatlands are found. This then leads to interbedded mineral sediment within the peat (e.g., Cooper et al., 2012; Sasaki and Sugai, 2018). The inclusion of mineral sediment within the peat profile changes the soil hydrologic properties (Duval & Waddington, 2018).

The climate changes expected to occur in the Rocky Mountains over annual timescales include warmer temperatures, reduced snowpacks, and reduced summer rainfall (Viviroli et al., 2011). Changes in climate are expected to impact peatlands primarily through a drop in the water table. This water table decline then causes physical changes to the peat, including compression and increased peat decomposition (Price and Schlotzhauer, 1999; Whittington and Price, 2006). These changes will alter the hydraulic characteristics of peat. As the peat decomposes and compresses, the porosity and hydraulic conductivity will decrease, reducing the peat storage capacity (Waddington et al., 2015). The effects of reduced storage capacity are expected to be amplified in mountain regions where peatland hydrology is dependent on the amount of recharge occurring within the watershed; even small changes to peatland water storage can be detrimental (Drexler et al., 2013). Reduced storage capacity in mountain peatlands will also impact the hydrology of adjacent foothills and lowlands as their primary water source is often located in the mountain ranges (Bullock & Acreman, 2003; Viviroli et al., 2011). However, relatively little is known about mountain peatland hydrology (e.g., Millar et al. 2018) and how changes brought about by climate shifts will impact the hydrology of these complex ecosystems. As such, some

properties can be simplified to single values which do not capture the dynamic nature of mountain peatlands (Millar et al, 2018).

Specific yield, a measure of how much water is available to drain under the influence of gravity, is often simplified by assuming water storage and release can be represented by a single value for a peatland (e.g., Sophocleous, 1985; Millar et al., 2018). This fails to consider the temporal and spatial variability that is found within a fen. For example, it has been shown that depth within the soil profile can influence specific yield (e.g., Bourgault et al., 2016; Carlson-Mazur et al., 2013). Specific yield, and how it varies with depth, influences the role that mountain peatlands play in mitigating and sustaining high and low flows, respectively. Peatlands mitigate flood flows by acting as a storage space for water and can supply baseflow during low flows by acting as a water source (Bourgault et al., 2014). While research has been done to understand the storage capacity of peatlands across the globe, most of the research is focused on peatlands in the boreal forest (e.g., Isabelle et al., 2018). Although there are examples of studies that examine water storage capacity in mountain peatlands (e.g., Valois, et al., 2020), there has yet to be consideration of how soil profile complexity influences these hydrologic properties.

Research is needed to examine the complexity of mountain peatlands in relation to their water storage capacity. In response, the following question is posed: How does soil profile complexity, typical of mountain peatlands, influence their water storage capacity? It is hypothesized that specific yield will not be depth-dependent, as is the case for peatlands with continuous peat soil profiles, owing to spatial variations in interbedding of mineral materials in the peat matrix. To test these hypotheses, the following objectives will be met:

- (1) estimate the specific yield of a mountain peatland under a dynamic water table,
- (2) determine spatial and temporal variability in specific yield, and
- (3) evaluate factors regulating specific yield.

## **2. LITERATURE REVIEW**

This literature review begins by introducing peatlands and their importance. This is followed by an introduction to peatlands in mountain regions. It then describes the hydrology of peatlands in general and in mountainous regions. This is followed by the identification of peatland sensitivity to changes in climate. The hydrologic properties of peat are then introduced, and the method used to evaluate specific yield is described. The literature review then concludes with a description of the research challenge and the gap filled by the research.

### **2.1 Peatland Overview**

#### **2.1.1 What is a Peatland?**

Peatlands are a type of wetland that forms due to the incomplete decomposition of plant material under near-saturated soil conditions (Xu et al., 2018). For a wetland to be considered a peatland it must have organic soils (i.e., soil with > 30% organic matter) that are greater than 40 cm in thickness and exist with high water tables causing permanently wet conditions (Whitfield et al., 2009). Worldwide, most peatlands formed 5 - 10 kya after the last glacial period (Whitfield et al., 2009), accounting for ~2.48% of global land cover (Xu et al., 2018). Peatlands cover 1.1 million km<sup>2</sup> of Canada's landmass (Whitfield et al., 2009) with the oldest peatlands located in the foothills and the Rocky Mountains of western Alberta and eastern British Columbia (Zoltai & Vitt, 1989). In mountain environments, different landforms can help to promote peatland formation on both local and landscape scales by influencing/creating ideal conditions for formation (Cooper et al., 2012). These landforms can include alluvial fans, colluvium deposits, eolian deposits, as well as moraines and other glacial features – most of which function as aquifers that store and provide groundwater to wetlands (Cooper et al., 2012).

#### **2.1.2 Ombrotrophic versus Minerotrophic Peatlands**

Peatlands are typically classified as bogs or fens, although there can also be peat swamps and marshes (National Wetlands Working Group, 1997). A bog is ombrotrophic, meaning that the peatland is fed entirely by precipitation (Whitfield et al., 2009). An abundance of *Sphagnum* moss is characteristic of bogs and the water table at (or just below) the ground surface and a moderate level of decomposition (Whitfield et al., 2009). Fens are classified as minerotrophic – this means that the primary source of water and nutrients are groundwater and surface water

rather than precipitation (Whitfield et al., 2009). Other characteristics of fens include poor decomposition of mosses and sedges and a fluctuating water table that is a few centimetres above or below the ground surface (Whitfield et al., 2009).

Fens can further be categorized into three groups: (1) intermediate fens, (2) rich or extremely-rich fens, and (3) iron fens and acidic geothermal fens (Cooper et al., 2012). Intermediate fens are found in locations where igneous rocks are dominant and have a pH between 5 and 6.5 (Cooper et al., 2012; Chimner et al., 2010). Rich and extremely rich fens form where carbonates are dominant and the pH is  $> 6.5$  (Cooper et al., 2012). Iron fens are located where iron-pyrite or volcanic vent sulphur emissions oxidize – allowing for the formation of naturally acidic (pH  $< 5$ ) fens (Cooper et al., 2012).

Fens can also be classified based on their setting – basin or slope. Basin fens can develop when sediment and later peat, fill depressions and small lakes (Cooper et al., 2012). Basin fens can fill with peat or contain water with mats of peat floating on top (Cooper et al., 2012). Slope fens are more common than basin fens as they occur in association with groundwater discharge areas (Cooper et al., 2012; Lowry et al., 2009). Slope fens can occur where perennial groundwater discharge occurs on hillslopes (with slopes  $< 30\%$ ) or in valley-bottoms where groundwater discharges from material such as till, alluvium, or colluvium deposits that act as aquifers (Cooper et al., 2012).

## **2.2 Why Peatlands are Important**

Peatlands provide benefits on global and ecosystem scales (Roets et al., 2008). On a global scale, peatlands store upwards of 600 Gt of carbon and thus play a vital role in the global carbon cycle (Yu et al., 2010). Though peatlands comprise a small portion of global land cover, they store approximately 10% of the world's freshwater resources (Rezanezhad et al., 2016). On ecosystem scales, peatlands provide clean drinking water and water storage, flood mitigation, and recreational and agricultural (livestock grazing) space (Reed et al., 2014). Bullock and Acreman (2003) analyzed 169 wetland studies to understand the role that wetlands play in the water cycle, concluding that: (1) they have a significant impact on the hydrological cycle, (2) their ability to reduce runoff or flood flow is dependent on the initial saturation conditions, (3) they experience significant evaporation, (4) many reduce downstream flow during dry years, and (5) many are fed by groundwater springs.



The importance of mountain regions and their water resources is globally acknowledged, as is the importance that wetlands play in the hydrologic cycle (Viviroli et al., 2011). Research conducted by Bourgault et al. (2014) found that peatlands play a vital role in maintaining the baseflow of adjacent rivers and cite that peatlands can provide as much as 41-100% of river baseflow. Because peatlands can store and provide large volumes of water, they play a significant role in the hydrology of mountain regions. Mountains are considered the "water towers" of the world (Viviroli et al., 2011). Viviroli et al. (2011) examined 11 case studies from across the world and found that 23% of mountain ranges, including the Canadian Rockies, are essential for providing water resources to their adjacent lowlands, while 30% played a supportive role.

### **2.3 Mountain Peatlands**

Peatlands are numerous in mountain regions such as the Rocky Mountains in the United States (US) and Canada (Chimner et al., 2010; Morrison et al., 2015). The role of mountain peatlands in the hydrologic cycle includes providing clean drinking water, mitigating flood flows, supplying adjacent river baseflows, and acting as a storage basin for freshwater (Reed et al., 2014). Peatlands in mountain regions typically form where breaks in slope cause groundwater discharge or where water can collect in valleys and basins (Chimner et al., 2010; Cooper et al., 2012). In both Canada and the US, the primary type of peatlands that can be found are fens (Chimner et al., 2010; Cooper et al., 2012; Morrison et al., 2015, Karran et al., 2018). The hydrology of mountain fens is influenced by the soil profile. The type of peat can cause changes in the hydraulic properties with depth. Many peatlands are comprised of either *Sphagnum* or sedge-derived peat and thus the decomposing material has different hydraulic characteristics (Liu & Lennartz, 2019); examples include porosity, bulk density, and saturated hydraulic conductivity.

In mountain regions, the soil profile of peatlands can be highly complex due to the dynamic geomorphological nature of mountain settings. Features such as alluvial fans, glacial features, river systems, and avalanches influence the soil profile (e.g., Sasaki and Sugai, 2018). The soil profile of mountain peatlands thus differs from those of other regions due to interbedded mineral sediments within the peat being deposited by these geomorphological features (Cooper et al., 2012; Wang et al., 2016).

## **2.4 Water Supplies to Peatlands**

### **2.4.1 General Peatland Hydrology**

A wetland can be both a source of water and provide storage for water (Streich & Westbrook, 2020). The water table remains at or near the surface due to the capillary tension between the peat particles (Thompson et al., 2007). The presence of a water table close to the surface of a peatland helps to maintain vegetation and thus renews the organic matter required for peat formation (Millar et al., 2018). Regardless of the topography, there is a complex interaction between surface water and groundwater resources (Winter, 1999).

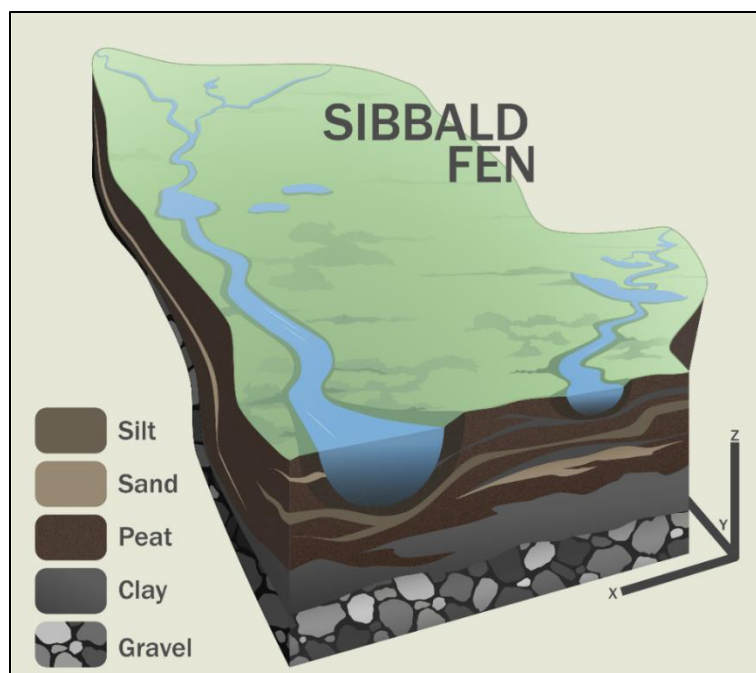
The ability to store and release water from peatlands is known as their water storage capacity. The water storage capacity of peatlands can impact the entire basin or watershed based on several factors such as those introduced by Buttle (2006) in the T<sup>3</sup> template. In the T<sup>3</sup> template, water storage capacity is characterized based on the interactions between the landscape and hydrology of the area. The T<sup>3</sup> template examines the interactions between (1) topology, the degree to which surfaces/materials present can control the vertical/lateral flow of water, (2) topography, the role of hydraulic gradients in moving water from the slopes to the stream/lake/wetland, and (3) typology, the hydrologic connectivity of the basin drainage network. It is important to understand the interactions of these hydrologic controls as they directly impact water storage capacity of peatlands by controlling the hydrologic connectivity of the basin or watershed to the peatland.

### **2.4.2 Mountain Peatland Hydrology**

Despite the volume of research on peatland hydrology increasing globally (Waddington et al., 2009), most of the information available does not establish a detailed understanding of peatlands in mountain settings. This lack of understanding includes everything from size, distribution, type, their role in carbon cycles, the hydrologic cycle, and their role in providing habitat for unique flora and fauna (Chimner et al., 2010). What is understood is that peatlands have three functional runoff states: (1) collecting/storing, (2) transmitting, and (3) contributing (Goodbrand et al., 2018; Spence & Woo, 2006). Though there are multiple controls on the runoff states (fen vs bog, position, and hydrologic characteristics of the peat), the position of the water

table has a significant influence on the state of a peatland (Goodbrand et al., 2018; Streich and Westbrook, 2020).

Mountain peatlands are characterized by active geomorphology, which leads to heterogeneous stratigraphy (Figure 2.1). Stratigraphy is defined as the study of the correlation between rock type, age, and position within the strata (Britannica, The Editors of Encyclopaedia). Since mountain peatlands are characterized by heterogeneous stratigraphy, this means that there are multiple layers of sediment within the peat profile (e.g., Morrison et al., 2015; Wang et al., 2016). This then causes the complex stratigraphy to alter the hydrology of mountain peatlands (Crosbie et al., 2005).



*Figure 2.1 Diagram of soil profile complexity in mountain peatlands using Sibbald Fen, located in the Canadian Rocky Mountains, as an example.*

*Illustration by A. Ronnquist, used with permission.*

## **2.5 Peatland Sensitivity to Changes in Water Supply due to Climate Change**

Wetlands continue to be one of the most heavily-impacted ecosystems in the world, with many either degraded or lost (Westbrook and Noble, 2013). Bourgault et al. (2014) identify three primary causes of wetland degradation: (1) urban expansion, (2) agriculture, and (3) climate change. Compared to others around the globe, peatlands in Canada are considered to be under the least pressure from development, though climate change poses an extreme threat (Whitfield et al., 2009). The peatlands which are most at risk from the negative impacts of climate change

are identified by Whitfield et al. (2009) as those located in the Hudson Bay Lowlands, the Mackenzie River Valley, and in northern Alberta and Manitoba. Global warming impacts on Canadian peatlands include their transition to significant greenhouse gas sources due to a drop in the water table (Millar et al., 2017), exacerbating global warming.

Perhaps the most substantial concern for peatlands under the stress of climate change will be the impacts to their water balance. Since mountain fens rely heavily on groundwater to support their unique ecology, they are highly sensitive to changes in groundwater supply – regardless of where recharge occurs within the watershed (Drexler et al., 2013). Having a low water table will reduce water release, which can have a detrimental impact on low flows (baseflow) in adjacent streams (Goodbrand et al., 2018). Reduced water tables due to climate change also can induce peat loss as decomposition increases (Millar et al., 2017). The water table, carbon budget, and peat accumulation of fens at lower elevations are most at risk from climate change due to already warmer temperatures and reduced snowpack (Millar et al., 2017).

Millar et al. (2018) identify snowmelt, winter precipitation and changes in the growing season to be potential drivers of how climate change can impact the water budget of mountain peatlands. Aldous et al. (2015) indicate changes to snowpacks (and thus fens) located in the subalpine zone as being high-risk. These snowpacks are at risk of shifting from seasonal (present all winter) to melting periodically, altering the snow-water equivalent that feeds many mountain streams, lakes, and wetlands during spring melt (Aldous et al., 2015). Variability in snowpack thickness due to climate change is also problematic as it can alter the depth of frost present in the underlying soil and the capacity for buffering surface runoff during snowmelt (Streich & Westbrook, 2020). Such changes subsequently reduce plant growth and restrict carbon sequestration (Cooper et al., 2019). To date, mountain climate change concerns have primarily focused on surface water and very little on groundwater, likely due to the complexity and challenges associated with site access and monitoring groundwater in mountainous terrain (Markovich et al., 2019).

## **2.6 Peatland Water Storage**

Peatlands can receive groundwater both laterally and vertically from aquifers located adjacent to and below the peatland, respectively (Quillet et al., 2017). Shallow water tables are characteristic of peatlands and are maintained by aquifer to peatland flows, capillary tension

(Bourgault et al., 2019) and surface water inputs (Drexler et al., 2013). In wet years, the shallow water table is typically maintained near the surface homogeneously throughout a fen; in dry years the water table is usually only maintained near-surface flows (Duval & Waddington, 2011; Guan et al., 2010). This is important for flow regulation in nearby streams, as rivers and peatlands often influence the flow of these channels. During wet years, peatlands help mitigate high flows by storing water that would otherwise contribute to flooding downstream (Bourgault et al., 2014; Streich & Westbrook, 2020). The opposite is true during low flows; peatlands release water to support baseflow of adjacent rivers and streams – providing up to 100% of baseflow (Bourgault et al., 2014; Streich & Westbrook, 2020). Thus, understanding how peatlands store and release water is crucial to understanding their role in the hydrologic cycle (Ferlatte et al., 2015; (Reed et al., 2014).

### 2.6.1 Hydraulic Characteristics of Peat

The hydraulic properties of peat are dependent on the vegetation type and the degree of peat decomposition (Rezanezhad et al., 2016). The porosity of peat is typically  $\geq 80\%$ . This means that there are many void spaces and larger pores present. Porosity,  $\phi$ , is typically calculated as:

$$\phi = (\rho_m - \rho_b) / \rho_m \quad (2.1)$$

where  $\rho_m$  is the density of the soil particles, and  $\rho_b$  is bulk density. However, Rezanezhad et al. (2016) identify peat as being a “dual-porosity medium” in which there is a mobile region where water and solutes move easily and an immobile region with “negligible fluid flow velocity.”

The depth of the water table provides insight into many peatland hydrologic variables such as saturation, runoff, and soil structure which in turn control porosity (Waddington et al., 2015). As depth within the peat profile increases, the degree of decomposition and compression typically increases, and porosity and saturated hydraulic conductivity decrease (Rezanezhad et al., 2016). This means that as the water table drops, water flows through the peat at a slower rate. Saturated hydraulic conductivity,  $K_{sat}$ , is a measure of how easily water can flow through saturated porous media (Dingman, 2015).  $K_{sat}$  can be characterized using Darcy’s law:

$$K_{sat} = q / \left( \frac{dH}{dx} \right) \quad (2.2)$$

where  $q$  is specific discharge,  $dH$  is the change in hydraulic head, and  $dx$  is the distance over which the groundwater flows (Dingman, 2015).

A related hydraulic characteristic of peat is its ability to store and release water. This is referred to as water storage capacity. The “measure of the volume of water that will be discharged from an aquifer per unit area of the aquifer and per unit reduction in hydraulic head” is referred to as storativity (Freeze & Cherry, 1979: 60). Storativity in unconfined aquifers can be calculated as:

$$S = S_s \left( \frac{\Delta V_w}{V} \right) \quad (2.3)$$

where  $S_s$  is specific storage,  $\Delta V_w$  is the volume of water discharged, and  $V$  is the total volume of soil drained per decline in the water table (Hogan, 2006).  $S_s$  is the volume of water removed from a volume of aquifer for a unit change in head and can be calculated by:

$$S_s = \rho_w g (\alpha + \phi \beta) \quad (2.4)$$

where  $\rho_w$  is the density of water,  $g$  is gravity,  $\alpha$  is the compressibility of the soil, and  $\beta$  is the compressibility of water (Freeze & Cherry, 1979). In unconfined aquifers, such as peatlands,  $S_s$  is equivalent to specific yield since the compressibility of the aquifer is often negligible, except when there is substantial swelling and shrinkage of the peat (Dettman & Bechtold, 2016). Fen water storage and release are controlled by the shrinkage and swelling of peat (Dettman & Bechtold, 2016), altering the pore size, water retention, hydraulic conductivity, and specific yield (Price & Schlotzhauer, 1999). Specific yield,  $S_y$ , is defined as “the volume of water that an unconfined aquifer releases from storage per unit surface area of aquifer per unit decline in the water table” (Crosbie et al., 2005) and is calculated using:

$$S_y = \frac{V_y}{V_t} \quad (2.5)$$

where  $V_y$  is the volume of water drained by gravity, and  $V_t$  is the bulk volume of soil. The change in the water table causes a change in the amount of water available to release from storage from an unconfined aquifer – such as a fen (Figure 2.2).  $S_y$  is directly related to porosity through specific retention,  $S_r$ . The relationship between the three variables is:

$$S_y = \phi - S_r \quad (2.6)$$

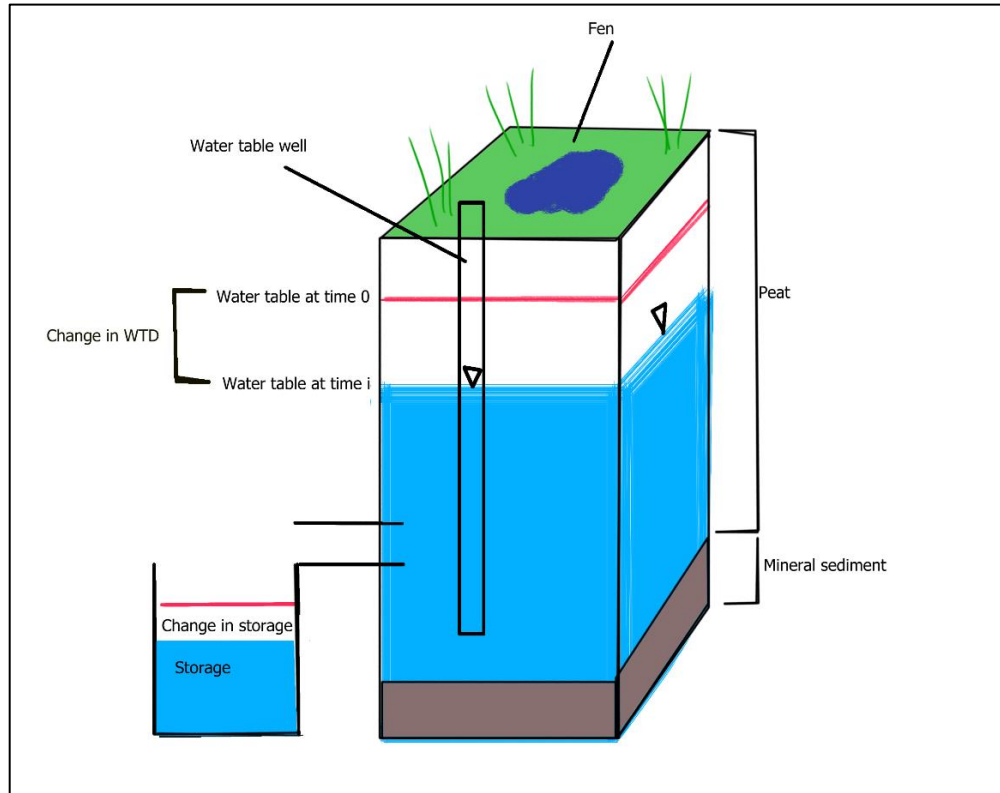
where  $S_r$  is a measure of how much water the soil can hold against the force of gravity; it is also sometimes referred to as matric potential and is calculated as:

$$S_r = \frac{V_r}{V_t} \quad (2.7)$$

where  $V_r$  is the volume of water held by gravity. Since fens can be connected to and function as unconfined aquifers (Ferlatte et al., 2015), we can apply these definitions to fens as a whole and examine how they interact with the water table. We can calculate the amount of water lost from storage based on the storage coefficient ( $S_y$  for unconfined aquifers), fen area and change in water table using the equation:

$$V_{water} = S_y A \Delta WTD \quad (2.8)$$

where  $A$  is area in  $m^2$  and  $\Delta WTD$  is change in water table depth (WTD) between time 0 and time  $i$  in m (Figure 2.2).



*Figure 2.2 Visual representation of how to calculate the amount of water lost from storage in a peat column due to a change in the water table.*

The relationship between depth below the ground surface and  $S_y$  is well established (e.g., Gillham, 1984; Healey & Cook, 2002; Crosbie et al., 2005; Bourgault et al., 2016; Bourgault et al., 2018).  $S_y$  has been shown to vary up to two orders of magnitude within the top meter of peat (Bourgault et al., 2019; Bourgault et al., 2016). Healey & Cook (2002) also found that  $S_y$  can also be a function of time, and Bourgault et al. (2018) found that  $S_y$  is typically greater at night than during the day. This is due to the water table being drawn down during the day from evapotranspiration, ET, and groundwater fluxes replenishing the peatland at night (Carlson-Mazur et al., 2013). Since  $S_y$  is depth-dependent, we can make assumptions regarding the meaning of  $S_y$  values in relation to the water table.  $S_y$  values  $>1$  are indicative of uphill surface water inputs or precipitation redistribution, while values between 0 and 1 are indicative of precipitation filling soil pore spaces until a threshold of saturation is reached (Bourgault et al., 2016).

As depth within the peat profile increases, the peat humification and compression increase; this results in a decrease in porosity and thus  $S_y$  (Wong et al., 2009; Bourgault et al., 2018). Crosbie et al. (2005) showed  $S_y$  depth relationships varying between homogeneous and heterogeneous soil profiles (also Nelson et al., 2011), common in mountain regions. These differences in material come with different  $\phi$ ,  $S_r$ ,  $K_{sat}$ , and compressibility, all of which impact  $S_y$ . Wang et al. (2016) studied soil moisture in a mountain fen and found that more water is stored in peat underlain by mineral sediments than in continuous peat profiles. While water storage within the peat is vital for most of the growing season, the storage that clay and silt layers provide, restricting vertical groundwater flow and holding water for extended periods, benefits peatlands greatly during droughts and extended periods without rainfall (Valios et al., 2020).

### **2.6.2 Estimating Specific Yield from Water Table Records**

$S_y$  can be estimated using a variety of methods. These methods include empirical formulas (Hill & Durchholz, 2015), drainage experiments (Gribovszki, 2018; Bourgault et al., 2018), water balances (Seraphin et al., 2018; Gribovszki, 2018), and other approaches (Moench, 1994; Bourgault et al., 2016). Similar to water balance approaches is a method emerging from the White Method (White, 1932) – the water table fluctuation (WTF) method (Bourgault et al., 2016). The WTF method involves calculating  $S_y$  from changes in the water table occurring

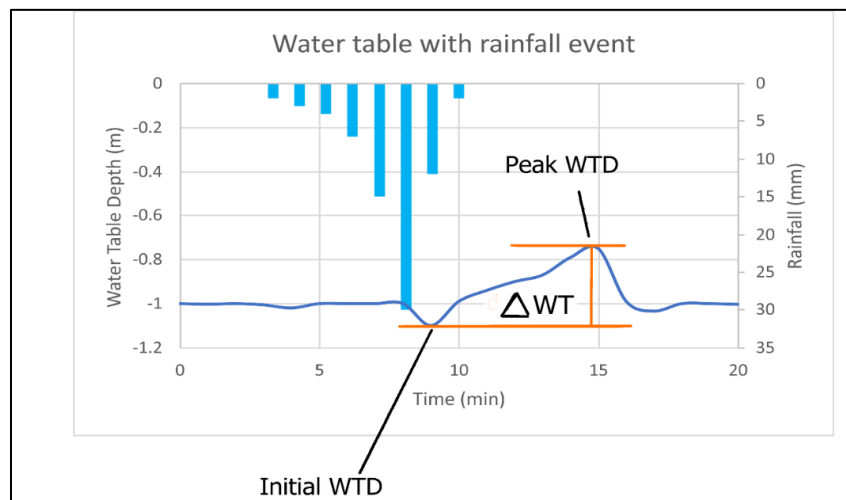


during rain events based on rainfall event totals (mm) and changes in water table depth. The WTF method has been utilized frequently to estimate recharge (e.g., Crosbie et al., 2019). In the WTF method,  $S_y$  is dependant on water table depth, the time between measurements, and antecedent conditions (Crosbie et al., 2019). The WTF method has several benefits. It is simple to calculate, relying on field observations of the water table that are often collected for other purposes, and so does not require complex field measurements or experiments in the laboratory. However, the drawbacks of estimating  $S_y$  via the WTF method is that it does not consider evapotranspiration or water held in the capillary zone and requires high-frequency measurements.

In the water table fluctuation method, specific yield,  $S_y$ , is calculated as the total rainfall that fell during an event, and the change in water table depth is calculated as the difference in the water table at the peak following the rainfall event minus the initial water table depth (Bourgault et al., 2016):

$$S_y = P/\Delta WTD \quad (2.9)$$

where  $P$  is rainfall, and  $\Delta WTD$  is the change in water table depth. An example of how to extract the water table fluctuation following a rainfall event from a hydrograph can be seen in Figure 2.3.



*Figure 2.3 Diagram depicting how to extract the change in water table following a rainfall event from observations of water table depth (line) and precipitation (bars).*

## 2.7 Research Challenge

Fens are among the most common peatlands found in mountain regions, and their hydrology is very different from those more commonly studied due to the complex nature of their soil profiles (Wang et al., 2016). The hydrological importance of fens and the role the water table plays are well established in the literature. An example of such is the crucial characteristic of mountain fens' ability to store and release water; this is typically referred to as the storage coefficient or specific yield. In the literature, when  $S_y$  is considered, it is often referred to as a single value or falling along a depth-dependent scale within the peat profile. It is important to understand the  $S_y$  of mountain peatlands because it controls how water is stored and released over time and space. This is critical in determining the ability of peatlands to sustain their unique biodiversity, maintain the integrity of the peat, and to support adjacent rivers and streams during low flows. Another important reason for developing a better understanding of specific yield in peatlands is to better represent water storage and release in regional hydrological models. By answering the research question, an understanding of how  $S_y$  varies within the complex environmental conditions that are characteristic of mountain fens will have been established.

### 3. METHODS

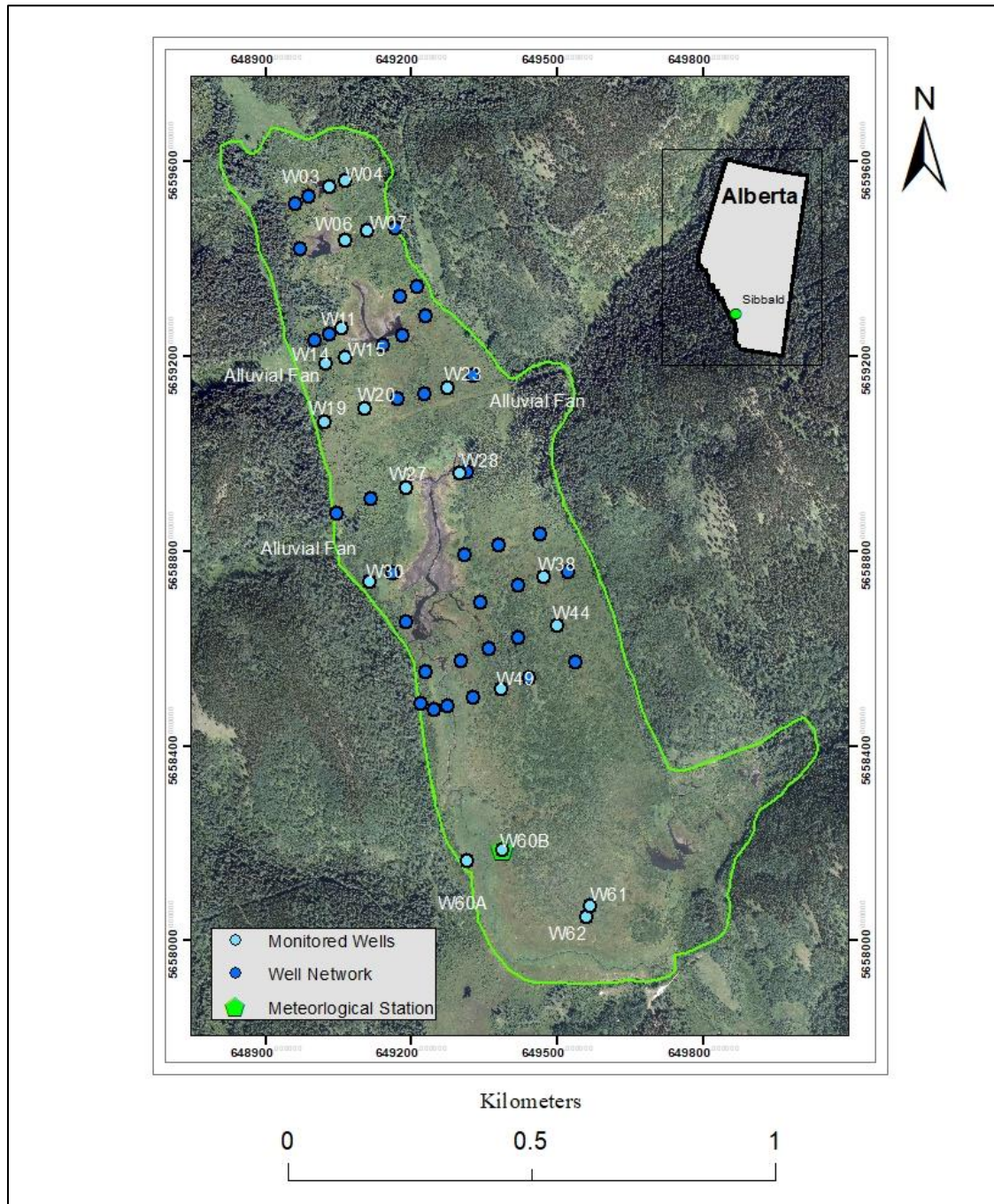
The water storage capacity of a mountain fen was studied. The research design relied on using existing observations of water table and precipitation to estimate spatial and temporal variations in  $S_y$  via the water table fluctuation method (White, 1932). This chapter describes the study site, the observational data, the procedure for estimating  $S_y$ , and the data analysis tools used.

#### 3.1 Site

The research was conducted in the southern Canadian Rocky Mountains in Alberta at the 1.3 km<sup>2</sup> Sibbald Fen (Figure. 3.1) (51°03'29.38" N, 114°52'11.66" W) (Westbrook & Bedard-Haughn, 2016). The fen is located approximately 70 km west of Calgary at a mean elevation of 1490 m asl. The primary outflow for the fen is Bateman Creek (Streich & Westbrook, 2020). Bateman Creek is a tributary of Jumpingpound Creek, which eventually flows into the Bow River. Sibbald Fen has been operated as a research site since 2006, with the primary focus being improved understanding of its formation and ecohydrology.

Several long-term research projects have been carried out at Sibbald Fen, and there is long-term monitoring of some hydrometric and hydrometeorological variables. Observations include inflow to and the outflow of Bateman Creek, water tables across a well network of 55 wells, and a standard meteorological station (Westbrook & Bedard-Haughn, 2016). The meteorological station collects air temperature, humidity, wind speed, soil temperature, moisture, heat flux, net radiation, atmospheric pressure, rainfall and snow depth data (Streich & Westbrook, 2020). The climate of Sibbald fen consists of relatively warm, dry summers and winters that promote mild freeze-thaw cycles due to the occurrence of warm Chinook winds from the West (Streich & Westbrook, 2020).

Land cover at Sibbald Fen (2017) is 65% sedges, 23% willows and 12% open water (Streich & Westbrook, 2020). Beneath the microtopography of hummocks and hollows is a layer of peat of variable thickness, up to and exceeding 5 m in the center of the peatland (Karran et al., 2018). The thinnest peat layers are located in the northern end of the peatland and the deepest peat is near the centre of the fen. The peat is primarily made up of sedges (*Carex aquatilis*) at shallow depths and *Sphagnum spp.* moss at depth (Wang et al., 2016).



*Figure 3.1 Map of Sibbald fen. Light blue wells indicate the wells studied from within the larger well network shown in dark blue. The meteorological station was relocated in 2017 from the W60A to the W60 B location.*

Lying beneath the peat is an alluvial aquifer (Toop & de la Cruz, 2002) composed of light grey clay with gravel. Groundwater resources for the fen are stored in and discharged through marine clays and alluvium deposits to the peatland (Streich & Westbrook, 2020). The

interbedded mineral sediment includes some sand, light and dark grey clays, and silt. Located at the margin between the peatland and hillslopes are six alluvial fans, two along the western edge and one on the eastern side (Figure 3.1). The underlying aquifer and presence of alluvial fans at Sibbald contribute to its complex soil profile. The well network used for instrumentation of the site was installed during the 2006 field season and well stratigraphy was recorded upon installation. Due to the slow nature of peat accumulation and lack of current geomorphic activity it is unlikely that the site would undergo any major changes to the well stratigraphy during the studied time frame.

## **3.2 Data**

### **3.2.1 Data Collection**

The long-term data sets for Sibbald Fen include hydrological and hydrometeorological data for 2006 to present. At the time of the start of this thesis, the data sets contained information up until 2019. Additional water table and vegetation data was collected from July through October of 2020. The subset of wells in the well network (Figure 3.1) that were instrumented in 2020 with automated level loggers were chosen based on those that provided the best overall coverage of the fen and past years' monitored wells. It is important to note that W60 was relocated during the 2017 growing season when the meteorological station was moved (see Streich and Westbrook, 2020) and thus has two locations, W60A (pre-2017 station move) and W60B (post-2017 station move), within the fen (Figure 3.1).

An overview of the wells monitored over the study period can be found in Table 3.1. Water table data for 2008 (W14, W23, W44 & W49) and 2009 (W3, W7, W11, W14, W15, W19, W23, W27, W38, W44 & W49) were recorded in cm and then converted to m. Water table data for 2014 (W60A) and 2015 (W60A) were recorded in m a.s.l. and converted to m in relation to ground surface. The remaining years of water table data (2017: W4, W7, W60B, W61 & W62, 2018: W60B, 2019: W60B, 2020: W4, W6, W20, W30, W44, W49, W60B, W61 & W62) were available in m relative to ground surface. During the summer of 2020, additional water table data for select wells in the Sibbald well network was collected using Solinst Leveloggers corrected for barometric pressure using a Solinst Barologger (installed at the fen MET station – W60B location) within the Data Wizard in Solinst (version 4.5.1). The 2020 water table values were then corrected for depth relative to the ground surface,  $x$  (m), using the calculation:

$$x = c + (b - a) \quad (3.1)$$

where  $c$  is the water level recorded by the Solinst Levellogger in m,  $b$  is the stick-up of the well above the ground surface in m, and  $a$  represents the total hanging length with which the logger suspended in the well in m (Figure 3.2).

*Table 3.1 Well monitoring overview for the study period.*

Year	Well #	Dates with data	Time-step
2008	W23	16/05 - 14/08, 19/08 - 11/10	1 hr
	W14	16/05 - 02/07	1 hr
	W49	05/05 - 07/08, 19/08 - 11/10	1 hr
	W44	20/05 - 13/08, 19/08 - 11/10	1 hr
2009	W3	12/06 - 06/10	1 hr
	W7	12/06 - 06/10	1 hr
	W11	12/06 - 06/10	1 hr
	W14	12/06 - 06/10	1 hr
	W15	12/06 - 06/10	1 hr
	W19	12/06 - 06/10	1 hr
	W23	12/06 - 06/10	1 hr
	W27	12/06 - 06/10	1 hr
	W38	12/06 - 06/10	1 hr
	W44	19/06 - 16/07, 31/07 - 20/09	1 hr
	W49	13/06 - 07/09	1 hr
2014	W60	26/06 - 24/09	15 min
2015	W60	26/06 - 27/08	15 min
2017	W4	28/06 - 14/08	1 hr
	W7	28/06 - 14/08	1 hr
	W60	25/07 - 15/08	1 hr
	W61	04/07 - 09/08, 10/08 - 15/08	1 hr
	W62	04/07 - 09/08, 10/08 - 15/08	1 hr
2018	W60	27/06 - 06/10	15 min
2019	W60	22/05 - 04/10	15 min
2020	W4	31/07- 11/08, 11/08-13/10	15 min
	W6	31/07 - 13/10	15 min
	W20	10/06 - 13/10	15 min
	W28	31/07 - 13/10	15 min
	W30	31/07 - 13/10	15 min
	W44	31/07 - 12/10	15 min
	W49	31/07 - 12/10	15 min
	W60	10/06 - 12/10	15 min
	W61	31/07 - 12/10	15 min
	W62	31/07 - 12/10	15 min

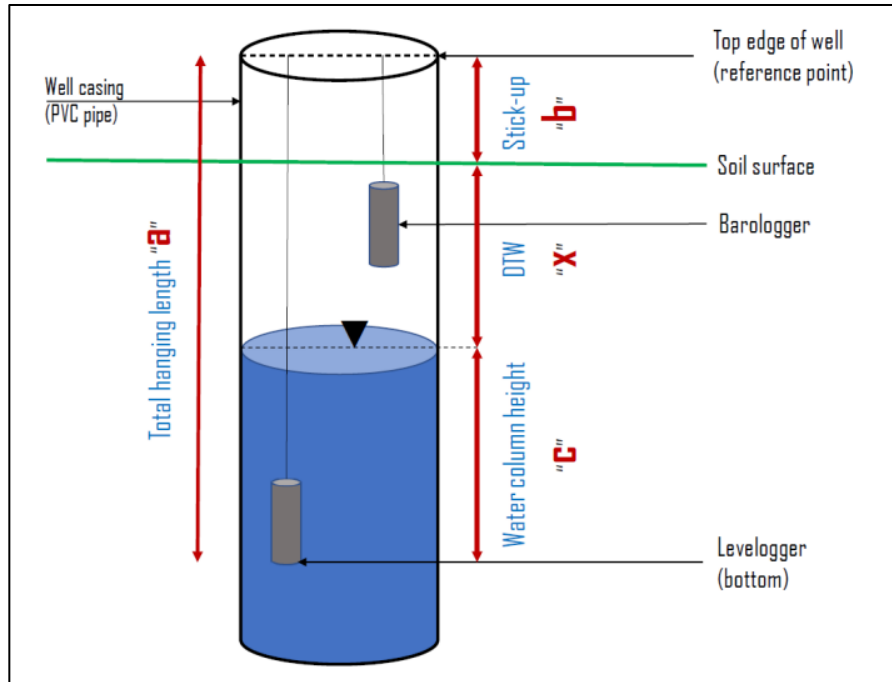


Figure 3.2 Diagram depicting the variables used to calculate water table depth,  $x$ .

Well stratigraphy (herein referred to as soil profile) was available from a database as soil information was compiled at the time of well installation. Soil profiles for the wells used in this study were visually compared (Figure 3.3B). Three different types of soil profiles were identified based on the arrangement of organic and mineral horizons (Figure 3.3A), loosely following the categorization of Wang et al. (2016). The first category of soil profiles consisted entirely of peat (PP; wells 20, 23, 27, 38, 44, 61, 62). The second category of soil profiles consists of peat interbedded with a thin silty mineral deposit referred to as peat-mineral-peat (PMP; wells 7, 28, 30, 49, 60B). The third category of soil profiles consisted of peat lying on a silty mineral deposit lying on gravel. These profiles were referred to as peat-mineral-gravel (PMG; wells 3, 4, 11, 14, 15, 19, 60A). PMG was most common where alluvial fans are located along the fen margin.



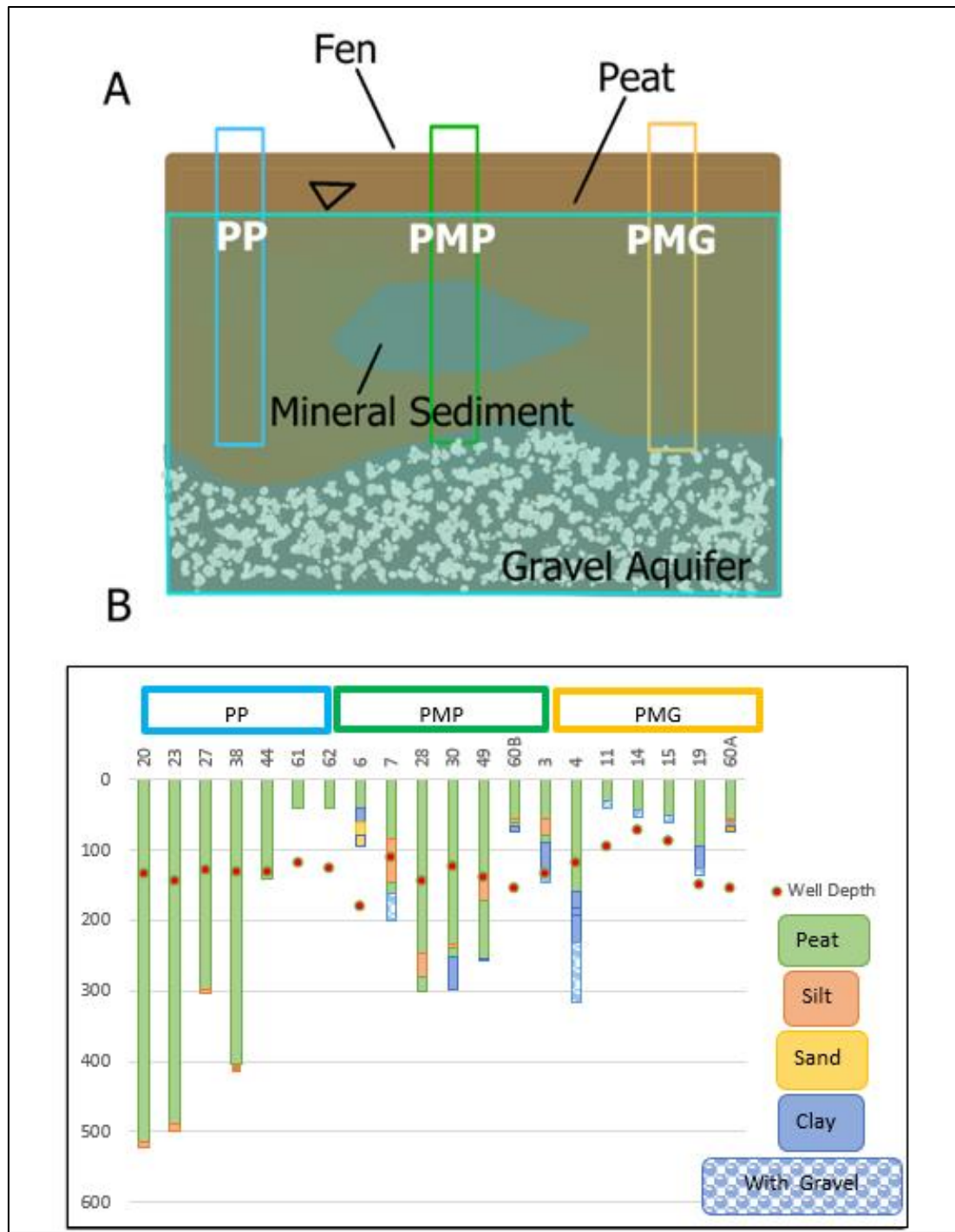


Figure 3.3 Simple diagram displaying the 3 soil profile classes (A) and visualization of soil profiles at each well monitored during the study period (B). Red circles indicate the completion depth of each well in panel B.



Vegetation cover at each well was observed during the 2020 field season. A 50 x 50 cm quadrat was placed directly West of each well and the percent canopy cover of herbs, moss, woody plants, and sedge was visually estimated. Photographs of each quadrat at the time of vegetation sampling were taken with a cell phone and archived. Vegetation data were analyzed as canopy cover of sedges, separated into the following three classes: <30, 30-60, and > 60% cover. As the study period extended over 15 years, aerial photographs from 2007 and 2017 were visually examined to assess whether there were noticeable shifts in dominant vegetation type across the fen. For example, the aerial photographs were examined to see if sedge was the dominant vegetation type had shifted to willows being the dominant vegetation type, and vice versa. Overall, no major vegetation changes were identified at the sites where the vegetation was observed in 2020.

Rainfall was available in hourly (2008, 2009, 2014, 2015, 2017, 2018), and 15-minute (2019, 2020) intervals from the fen meteorological station and was used in the calculation of  $S_y$ . Rainfall (daily) for the nearest Environment and Climate Change Canada weather station – Kananaskis (station 3053600, approximately 3 km west of the research site) (ECCC, 2020) were used to develop a precipitation index to assist in dividing the growing season into three categories. The index was created by calculating the standardized precipitation index (SPI) for one-month intervals using the calculation:

$$SPI = (P - P^*)/\sigma_p \quad (3.2)$$

where  $P$  is precipitation,  $P^*$  is mean precipitation for each month of the year and  $\sigma_p$  is the standard deviation of precipitation (Keyantash, J. & National Center for Atmospheric Research Staff). The SPI was then plotted in R using the SPEI package. Rainfall for 2008, 2019 and 2020 was available on site from a tipping bucket rain gauge. The rain gauge in 2008 was located at the old MET station location (UTM 11U 649314.4 N, 5658163 W). The rain gauge was moved in 2017 to the new MET station location (UTM 11U 649387.1 N, 5658186 W) (see Streich & Westbrook, 2020).

### 3.2.2 Data Analysis

#### 3.2.2.1 Calculation of Specific Yield

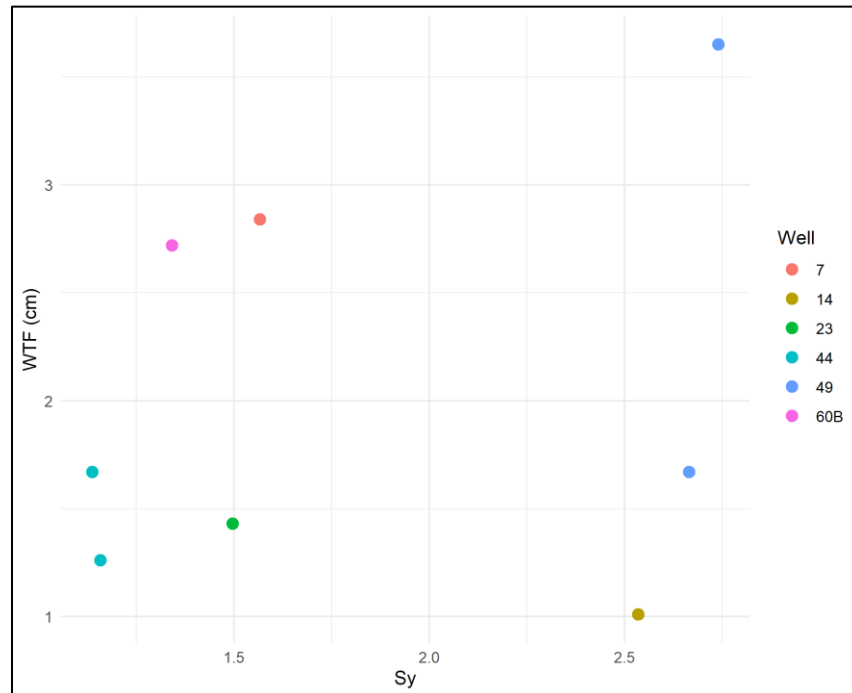
The water table fluctuation (WTF) method outlined in section 2.5.2 was used to calculate  $S_y$  at each well for each rainfall event during the period outlined in section 3.2.1. The water table fluctuation method was chosen over other methods, such as laboratory methods and other empirical formulas, because of the data available, the ease at which the method can be applied to long term datasets, and the applicability of the assumptions made. These assumptions include negligible runoff (i.e., that all rainfall becomes recharge) and that the time between rainfall initiation and water table rise is small enough that evapotranspiration, lateral groundwater flow, and water table recession are also negligible (Bourgault et al., 2016). In order to estimate  $S_y$  using the WTF method, rainfall events, initial water table and peak water table depths needed to be defined.

Rainfall events were extracted from the rainfall dataset (in section 3.2.1). For inclusion of a rainfall event in the analysis, an event had to meet three criteria. The first criterion for inclusion in the analysis was that event rainfall must be  $\geq 3$  mm and that the time between two periods of sustained rainfall must be less than 8 hours. In cases where there were more than 8 hours between rainfall observations, events were considered separately. The separation was determined by creating frequency distribution plots at 4-, 8-, 12-, 16-, and 24-hour separation to ensure that enough rainfall events were included for analysis. The second criterion for inclusion in the analysis was that the rainfall must have elicited a visual response in the water table (i.e., a  $\Delta WT \geq 10$  mm). The third criterion was that the water table must have been at or below the ground surface throughout the event. Events for which the water table was above the ground surface during the event were removed from the dataset as specific yield is equal to 1 in these cases. Out of all 827 events, 63.2% (79) of the rainfall events met all three criteria.

The initial and peak water table depths were extracted to calculate the change in the water table. This was done using a coding script written in R software (Appendix A). The script utilized the rainfall start time and scanned ahead in the water table depth data for each well to locate and record the peak and the time it occurred. It then scanned backwards from the peak to locate and record the water table's trough (and the time it occurred) and mark it as the initial water table depth. The water table change for each rainfall event was then calculated as the peak

minus the initial water table depth. From there, the water table fluctuation values were then scaled by total rainfall for each event and multiplied by 10 to obtain a value of change in the water table per 10 mm of rain ( $\Delta WT_s$ ) to aid comparison of  $S_y$  for rainfall events of different magnitude.  $S_y$  was then calculated from the unscaled  $\Delta WT$  and rainfall using equation (2.9). The bootstrap technique (10,000 iterations, resampled from the observations) was used to estimate the distribution of  $S_y$  for the fen. Bootstrapping was carried out using a script in R.

A total of 125 rainfall events met the first inclusion criteria for use in the calculation of  $S_y$ . However, 8 (6.4%) of these rainfall events led to estimates of  $S_y > 1$ , leading to values of  $S_y$  between 1.1 and 2.7 (Figure 3.4). The values of  $S_y > 1$  were not considered further as they violate the assumption of negligible runoff (Bourgault et al. 2016), leading to a data set of 79 events.



*Figure 3.4  $S_y$  and water table fluctuation relationship for all 8 rainfall events that produced a  $S_y > 1$  at their respective wells.*

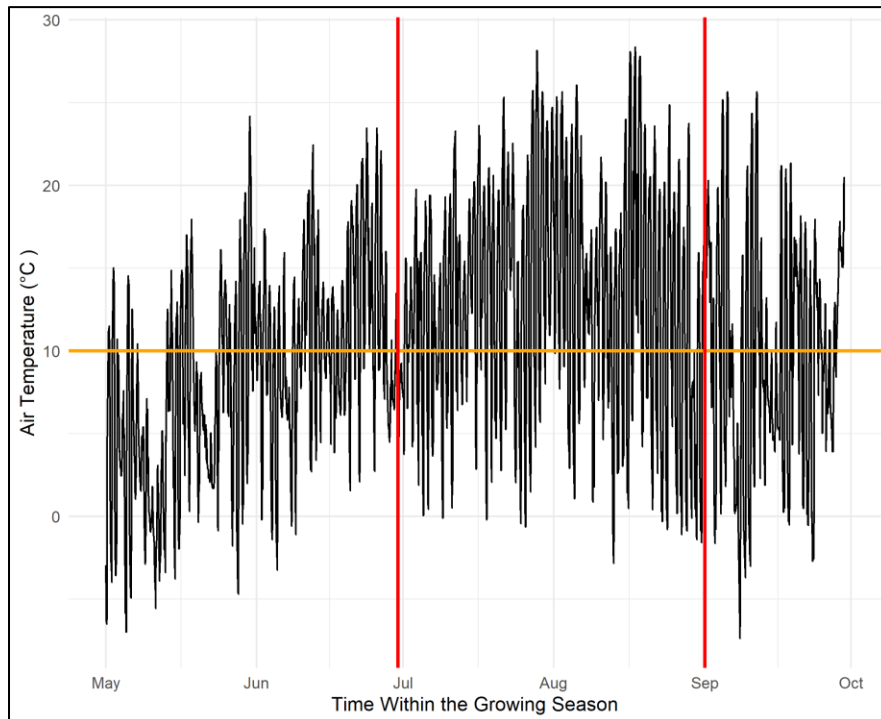
### **3.2.2.2 Spatial Variability of Specific Yield**

The spatial variability of  $S_y$  was determined by comparing values at each well using a one-way analysis of variance (Kruskal-Wallis test) followed by a pairwise comparison (Dunn test) in R to determine the statistical differences between wells. A rejection limit of 0.05 was used to determine significance in the statistical analysis.

The median values for each well were mapped using ArcGIS and then spatially interpolated via ordinary kriging in Surfer, Golden Software and plotted on a rectangular domain.

### ***3.2.2.3 Temporal Variability of Specific Yield***

The temporal variability of  $S_y$  was explored in two ways. One, the growing season was split into three time periods: May-June, July-August, and September. The time periods were identified by examining mean daily air temperature (Figure 3.5) and observing shifts in plant growth from photograph records (Figure 3.6). May-June was categorized by budding vegetation and mean daily air temperatures  $< 10^{\circ}\text{C}$  ( $8.4^{\circ}\text{C}$ ). July-August was categorized by green vegetation and mean daily air temperatures  $> 10^{\circ}\text{C}$  ( $13.0^{\circ}\text{C}$ ). September was categorized by senescing vegetation with mean daily air temperatures  $< 10^{\circ}\text{C}$  ( $9.9^{\circ}\text{C}$ ). A Kruskal-Wallis test followed by a pairwise comparison (Dunn test) post-hoc test in R was used to identify differences in  $S_y$  among the three time periods. Two, comparisons of  $S_y$  among years was carried out with a Kruskal-Wallis test followed by a pairwise comparison (Dunn test) post-hoc test in R.



*Figure 3.5 Average air temperature change for dividing the growing season. The orange line indicates  $10^{\circ}\text{C}$ , which was the threshold used to determine average air temperature differences between the three time period categories.*

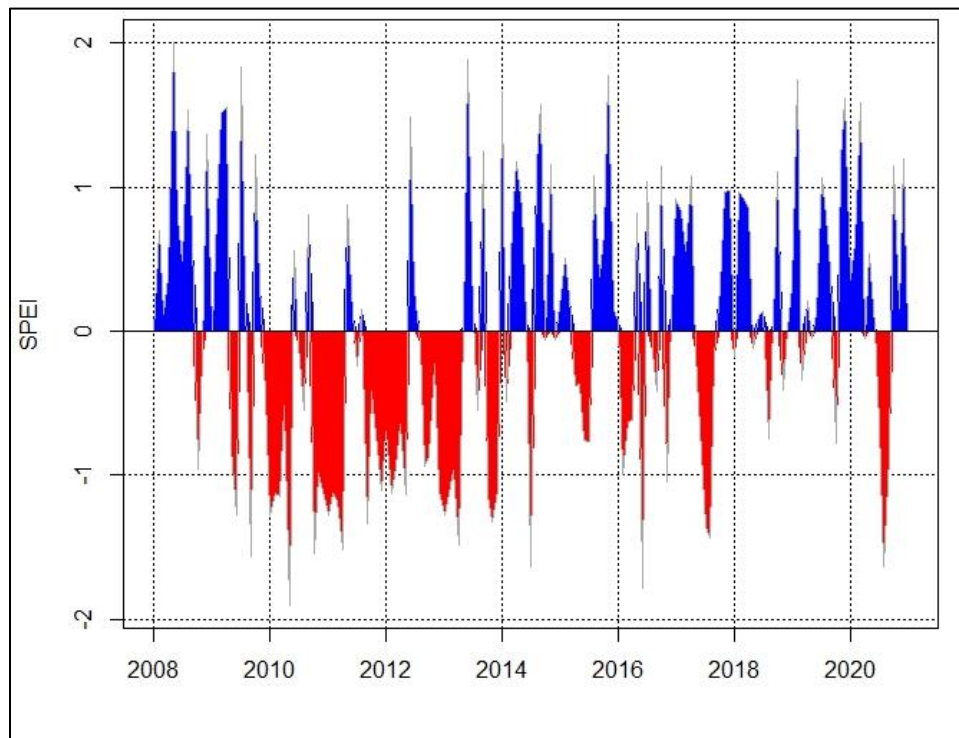


*Figure 3.6 Observed change in vegetation throughout the growing season at Sibbald Fen. A. May-June vegetation, B. July-August vegetation, and C. September vegetation.*

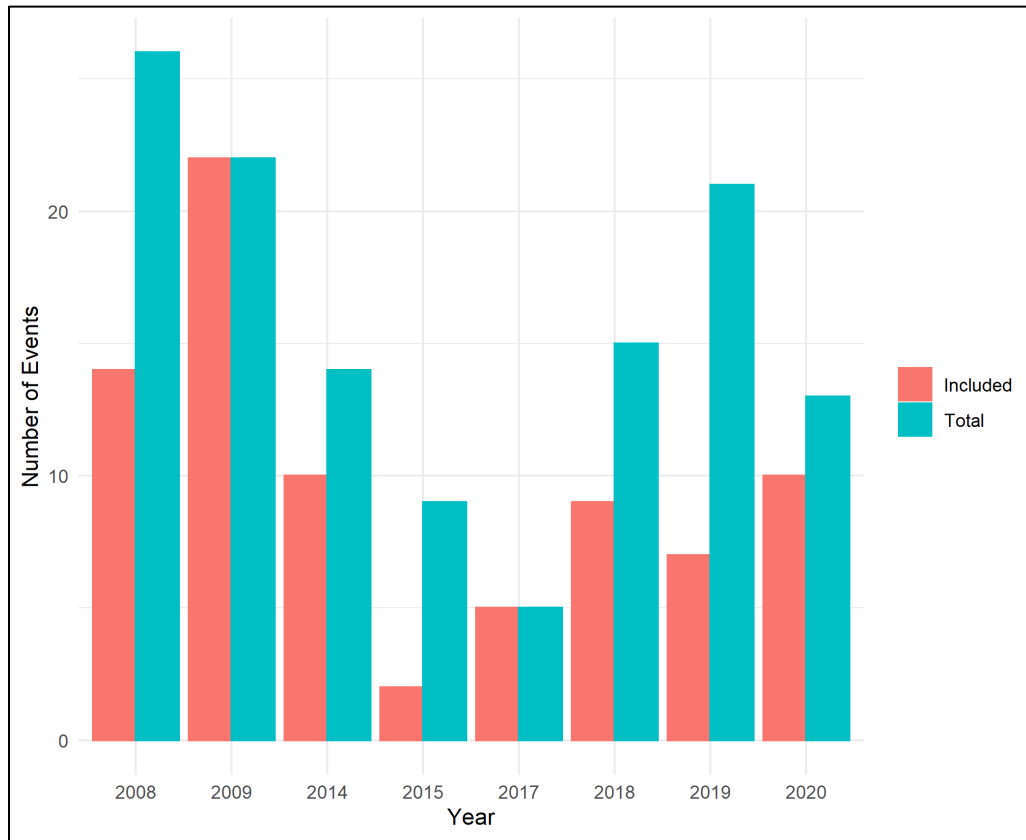
## 4. RESULTS

### 4.1 Rainfall Events

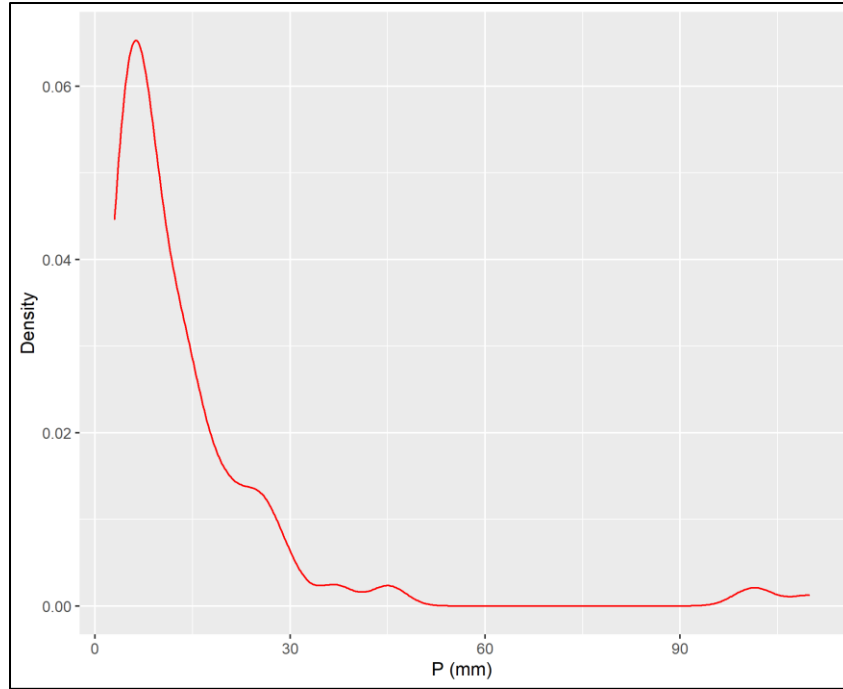
Results of the SPI analysis showed that 2008, 2009, and 2019 are wetter years than the other years studied (Figure 4.1). SPI values indicate the driest years were 2020 (-0.139) and 2017 (-0.104). A total of 125 rainfall events occurred during the period May 1<sup>st</sup> through October 31<sup>st</sup> in 2008, 2009, 2014, 2015, and 2017 through 2020 which fit the first criteria,  $P_t$  (Figure 4.2). There was an order of magnitude more rainfall events in 2008 and 2009 than in other studied years.  $P_t$  had a positively skewed distribution and ranged from 3.0 to 109.8 mm with a median of 8.9 mm (Figure 4.3). Only 79 of these rainfall events fit all three inclusion criteria for the study and were further considered, hereafter referred to as  $P_i$  (Figure 4.2).  $P_i$  ranged from 3.0 to 44.5 mm with a median of 7.9 mm; the distribution of  $P_i$  was positively skewed indicating that the majority of rainfall events were less than 10 mm. (Figure 4.4). The intensity of  $P_i$  ranged from 0.13 to 9.80 mm/h with a median of 0.81 mm/h (Figure 4.4). The greatest range of  $P_i$  occurred in August, with the smallest range occurring in October (Figure 4.5A). The highest median rainfall intensity occurred during October at 1.83 mm/h,  $z$ -score = 25.3,  $p$  = 0.00004 (Figure 4.5B).



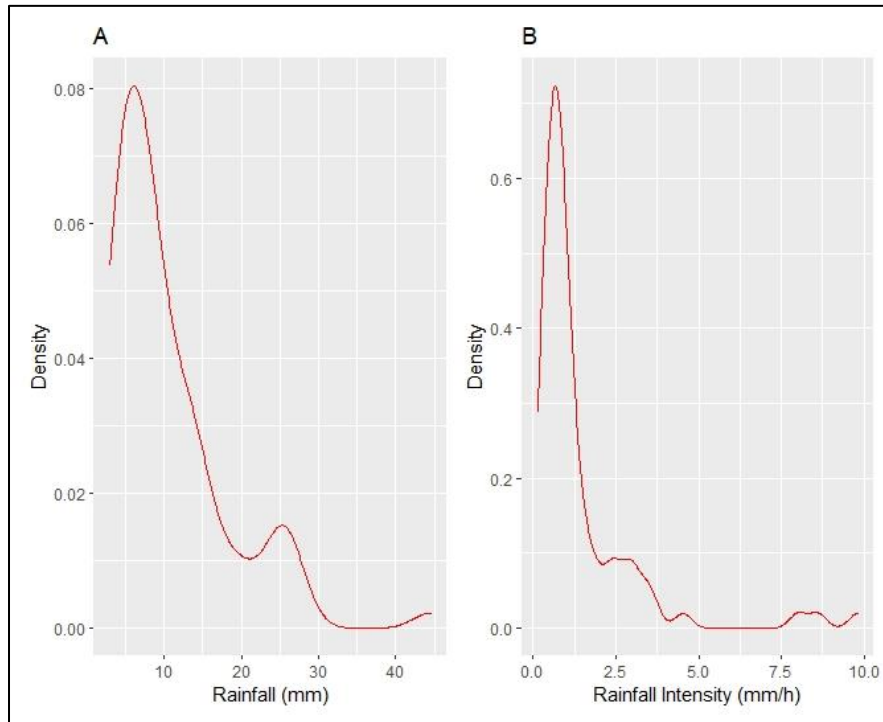
*Figure 4.1 SPI graph for 2008 through 2020.*



*Figure 4.2 Total number of rainfall events ( $P_t$ ) and number of rainfall events that fit the analysis inclusion criteria laid out in section 4.2.2.1 ( $P_i$ ) occurring between May 1st and October 31st of each studied year.*

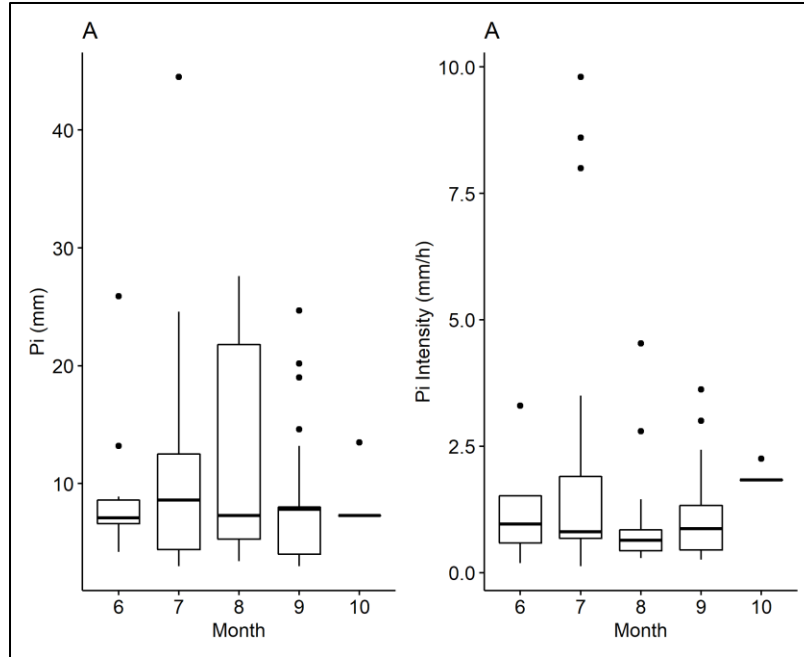


*Figure 4.3 Density distribution of all 125 rainfall events ( $P_t$ ) considered in this research.*



*Figure 4.4 Density distribution plots of rainfall events,  $P_i$  (A) and their intensity (B) used in the analysis.*





*Figure 4.5 Boxplots of the magnitude (A) and intensity (B) of  $P_i$  by month. The asterisks above each of the bars represents the level of significance between each pair. The fewer the asterisks, the closer the  $p$  value is to 0.05.*

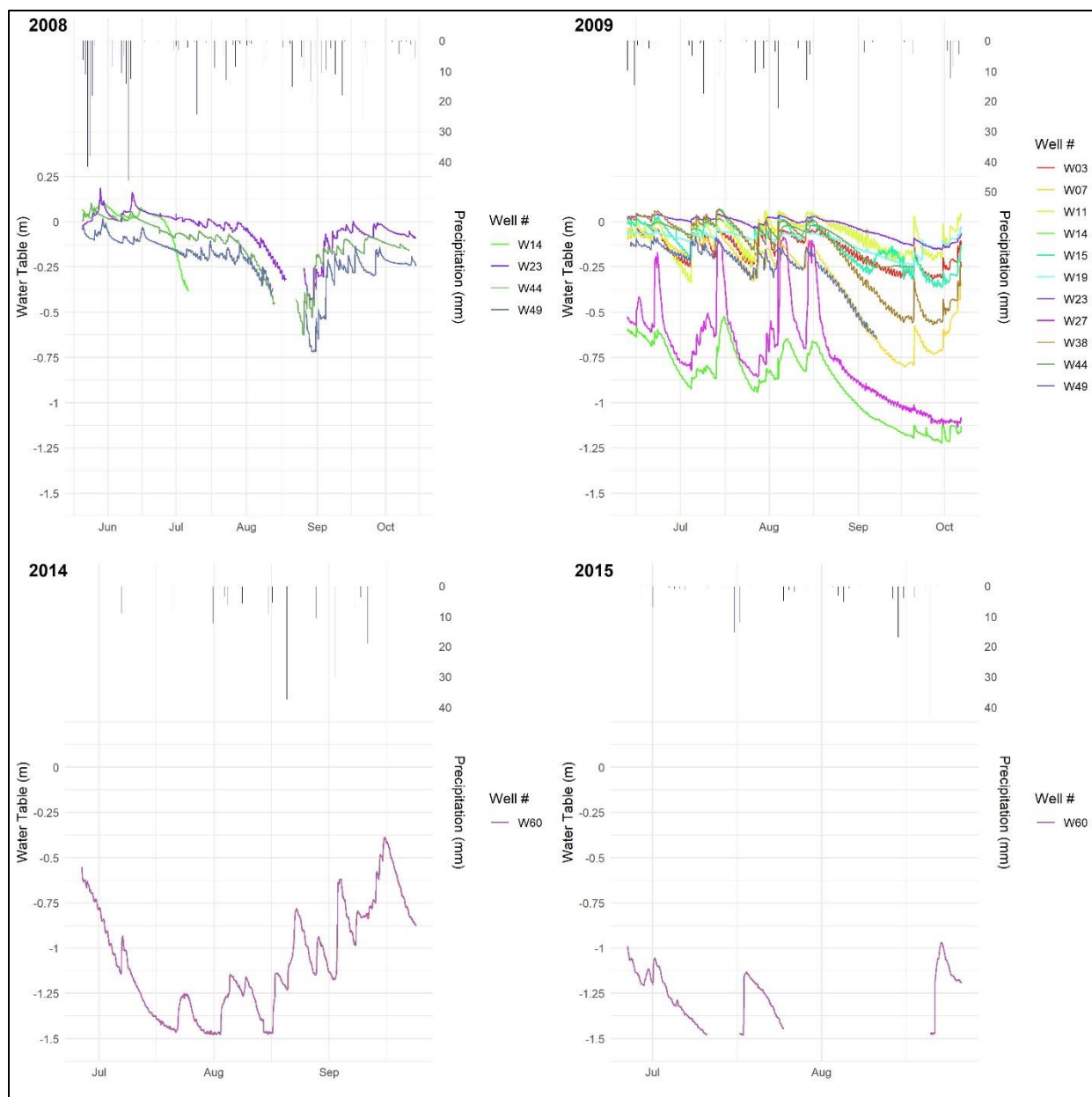
## 4.2 Water Table Fluctuations

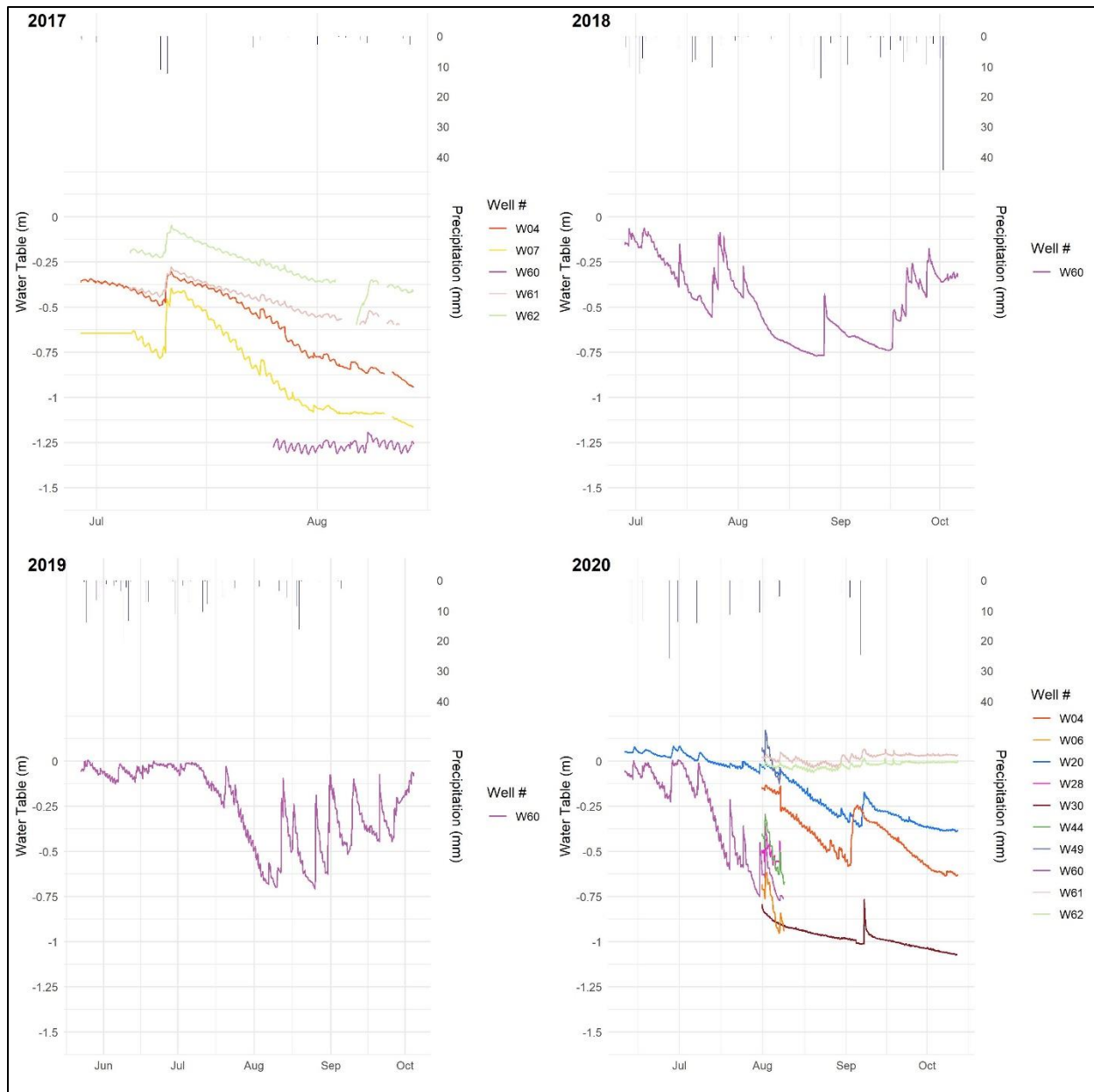
Over the growing season, the water table at all wells tended to experience a steep drop; an example of such can be seen in W60 during 2019 (Figure 4.5). A steep water table decline is regularly experienced at Sibbald Fen over the growing season (Karran et al., 2018). These declines were followed by a rise in the water table at a few of the wells occurring towards the end of August and the beginning of September (easily seen in W49 during 2008, W19 in 2009, W23 in 2009, and W60 in 2018 & 2019) (Figure 4.5). Water table depths were recorded at the onset of a rainfall event ( $WT_i$ ) and at the peak water table response ( $WT_p$ ). The distribution of  $WT_i$  is shown in Figure 4.6A, where  $WT_i$  was positively skewed and ranged from -1.47 m below the surface to 0.06 m above the surface with a median of -0.22 m. The distribution of  $WT_p$  is shown in Figure 4.6B where  $WT_p$  was also positively skewed and ranged from -1.26 m to 0.08 m with a median of -0.13 m.

The magnitude of water table changes for a rainfall event ( $\Delta WT$ ) ranged from 5.7 mm to 524 mm, with a median of 49.4 mm.  $\Delta WT$  scaled to a rainfall of 10 mm,  $\Delta WT_s$ , had a range of

0.038 mm to 6.24 mm with a median of 0.59 mm and had a negatively skewed distribution (Figure 4.7).  $\Delta WT_s$  varied from well to well, but with the greatest fluctuations occurring in wells 11, 38, 60A and 60B,  $z$  score = 56.5,  $p = < 0.001$  (Figure 4.8).

September had significantly lower  $WT_i$  and higher  $\Delta WT_s$  compared to the rest of the observation period (May-August). The median water table depth for May-June (-9.89 cm) were significantly different than those for July-August (-12.11 cm) and September (-31.87 cm),  $z$ -score = 12.1,  $p = 0.002$  (Figure 4.10A). Similarly, median  $\Delta WT_s$  for May-June (5.14 cm) and July-August (5.58 cm) were similar, while September had a median WTF nearly double that of May-August at 10.61 cm,  $z$ -score = 7.7,  $p = 0.021$  (Figure 4.10B).  $WT_i$  was significantly different between years,  $z$ -score = 39.9,  $p = < 0.001$  (Figure 4.11A). The  $WT_i$  for both 2015 and 2014 was less than that of the other studied years, with medians of -120.09 and -118.13 (Figure 4.11A). Between years, the only  $\Delta WT_s$  that were significantly different from one another were 2009 and 2014,  $z$ -score = 25.1,  $p = < 0.001$  (Figure 4.11B). The soil profile influences on  $\Delta WT_s$  showed a significant difference between PMG and PP, as well as PP and PMP soil profiles,  $z$ -score = 56.5,  $p = < 0.001$  (Figure 4.12A). The largest  $\Delta WT_s$  were found in PMP soil profile (median = 5.090 cm) while PMG and PP had lesser and similar  $\Delta WT_s$  (PP median = 5.630, PMP median = 11.03). It was found that % sedges did not have an impact on  $\Delta WT_s$  (Figure 4.13A).





*Figure 4.6 Well hydrograph and hyetographs for each year and well during the study period. Gaps in the hydrograph record are periods of no data.*

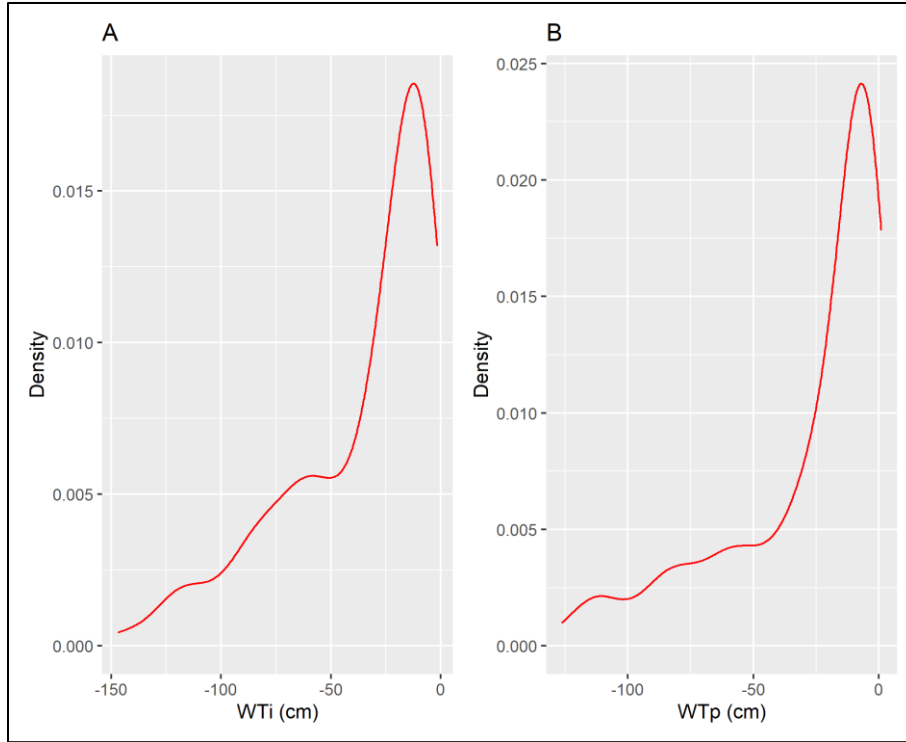


Figure 4.7 Density distribution of initial water table,  $WT_i$  (A) and peak water table,  $WT_p$  (B) for the rainfall events used to calculate specific yield.

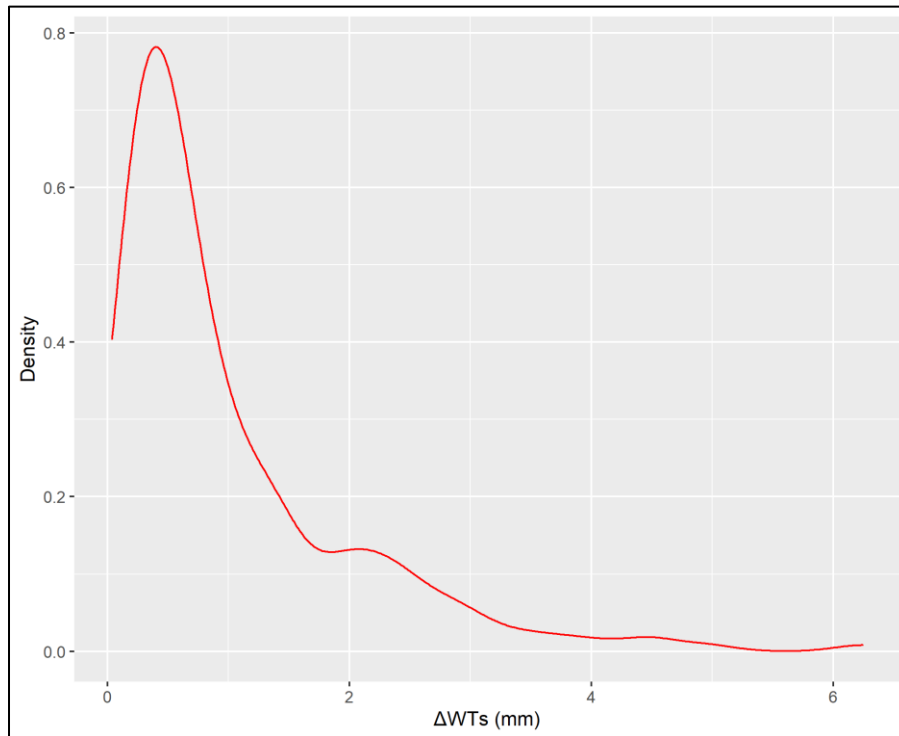


Figure 4.8 Density distribution of the magnitude of water table fluctuation for a rainfall event,  $\Delta WT_s$  per 10 mm of rainfall.

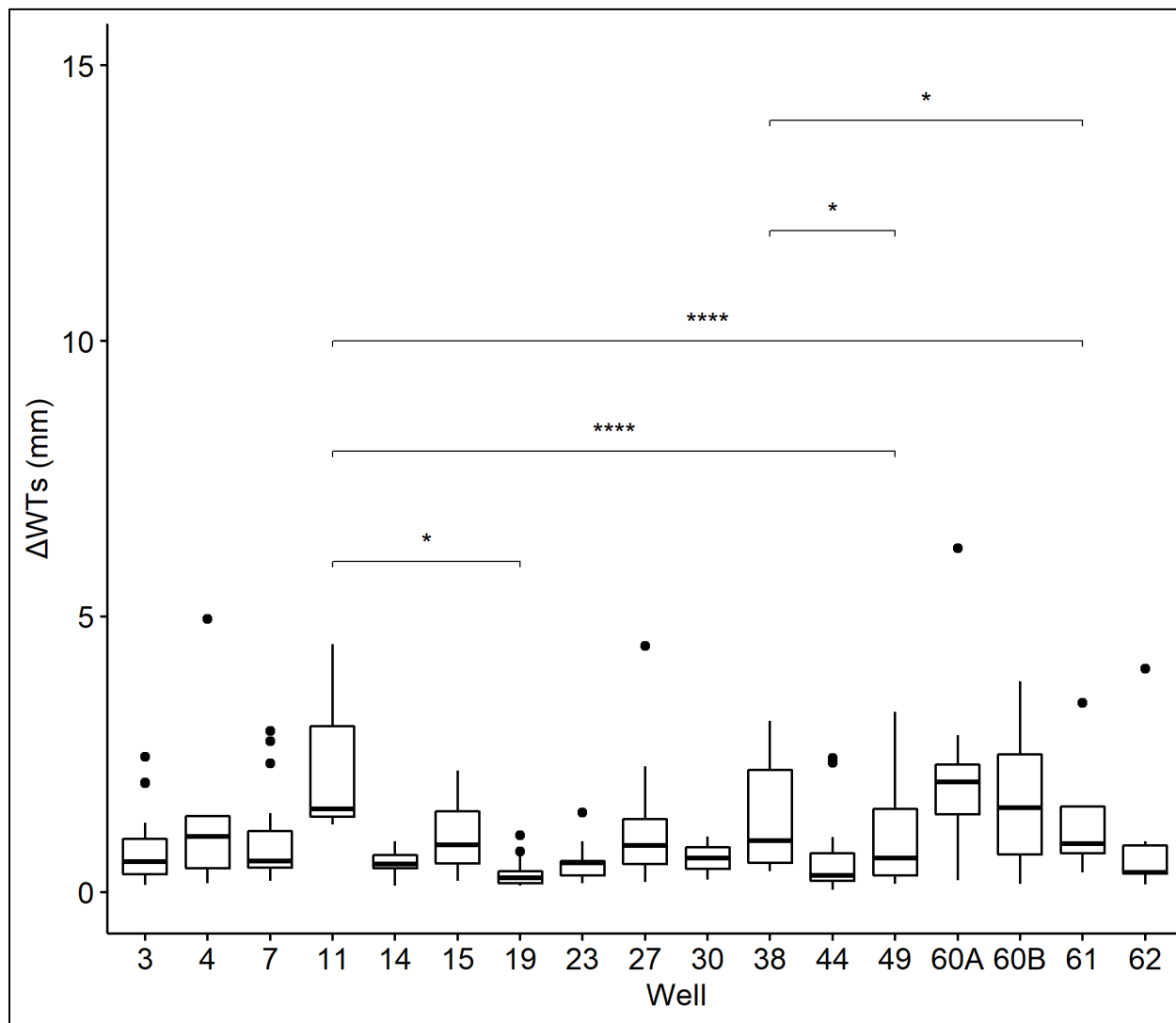


Figure 4.9 Boxplots of change in water table ( $\Delta WT_s$ ) per 10 mm of rainfall for each well site studied. The asterisks above each of the bars represents the level of significance between each pair. The fewer the asterisks, the closer the  $p$  value is to 0.05.

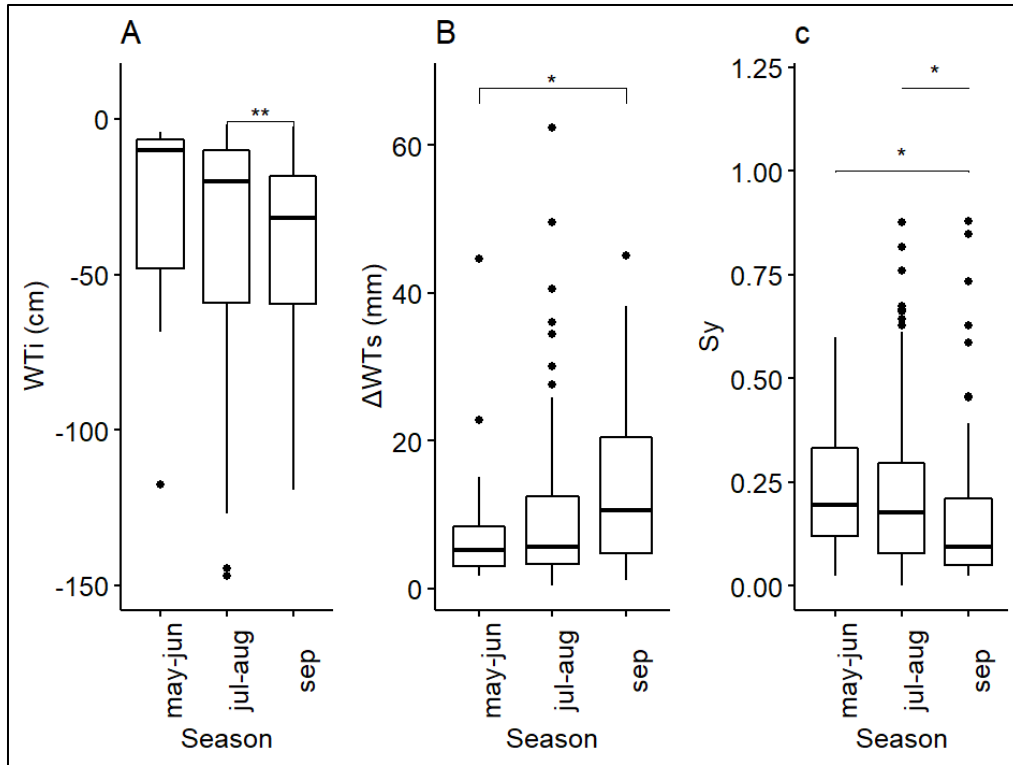


Figure 4.10 Boxplot of  $WT_i$ ,  $\Delta WT_s$ , and  $S_y$  throughout the progression of the growing season. The asterisks above each of the bars represents the level of significance between each pair. The fewer the asterisks, the closer the  $p$  value is to 0.05.

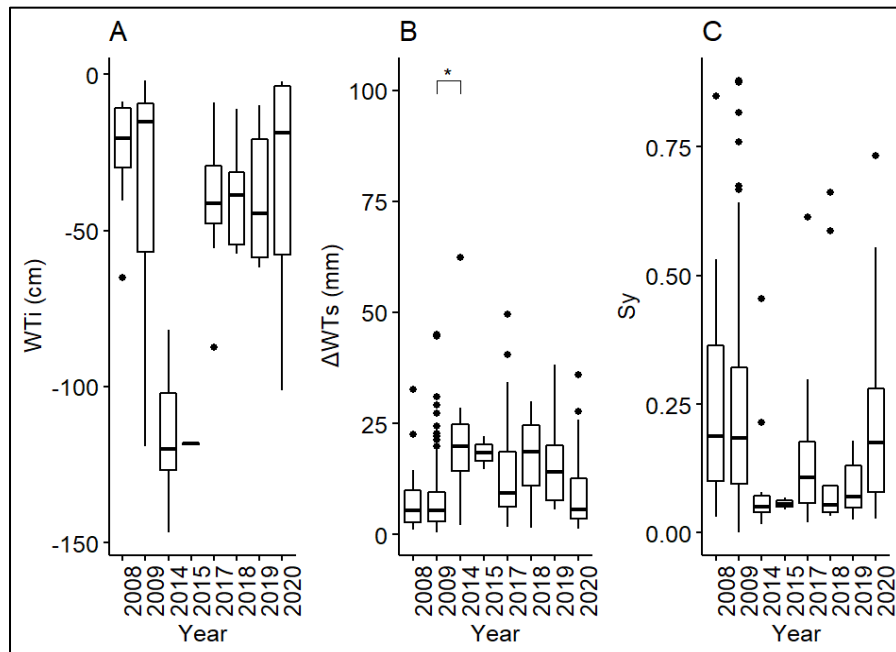


Figure 4.11 Boxplot describing the distribution of  $WT_i$  (A),  $\Delta WT_s$  (B), and  $S_y$  (C) values between the years studied. The asterisks above each of the bars represents the level of significance between each pair. The fewer the asterisks, the closer the  $p$  value is to 0.05.

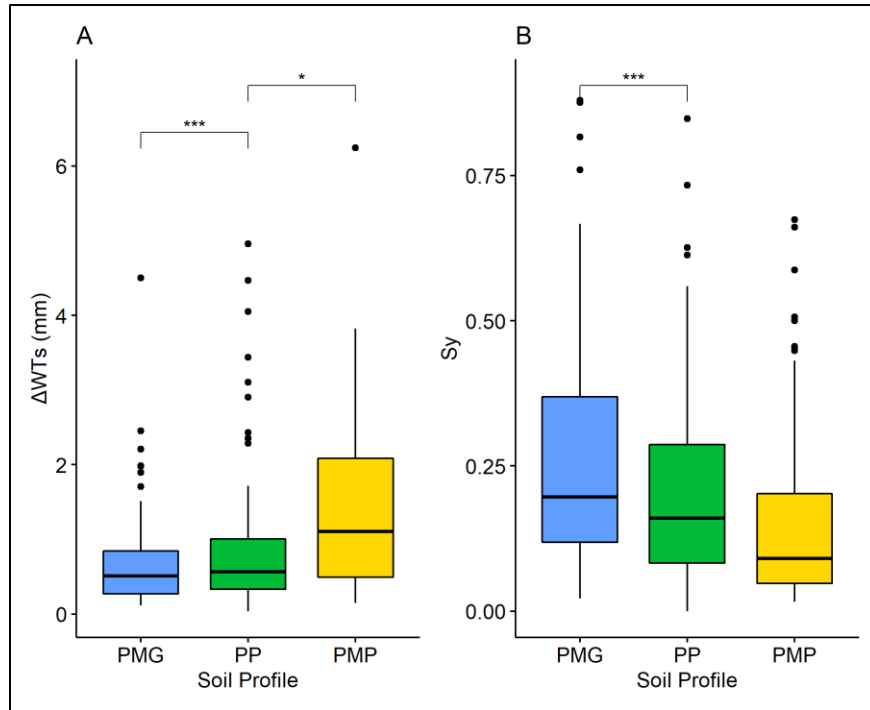


Figure 4.12  $\Delta WTs$  and  $S_y$  variation by soil profile. The asterisks above each of the bars represents the level of significance between each pair. The fewer the asterisks, the closer the  $p$  value is to 0.05.

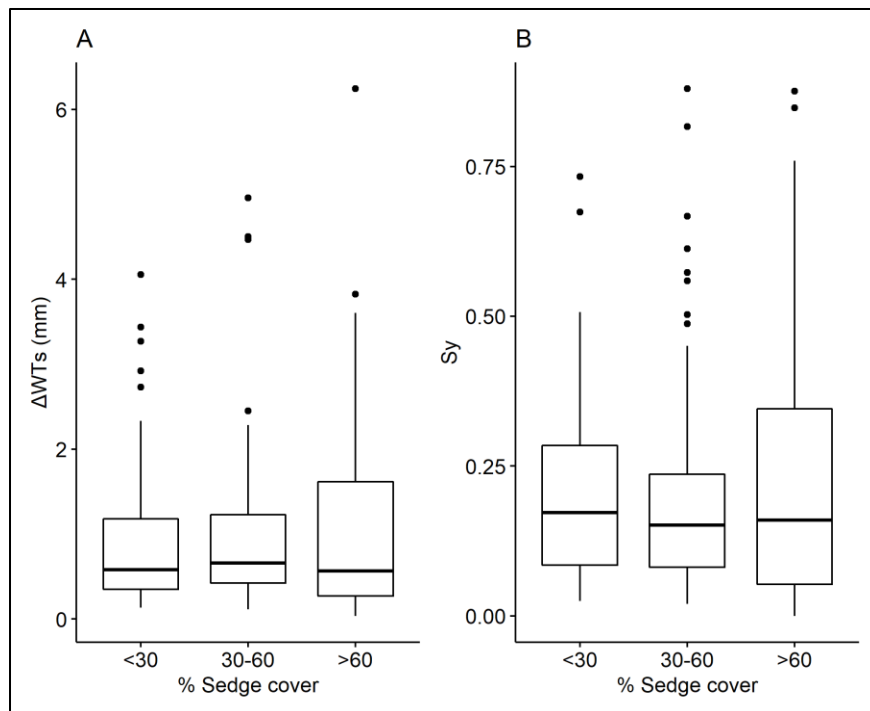
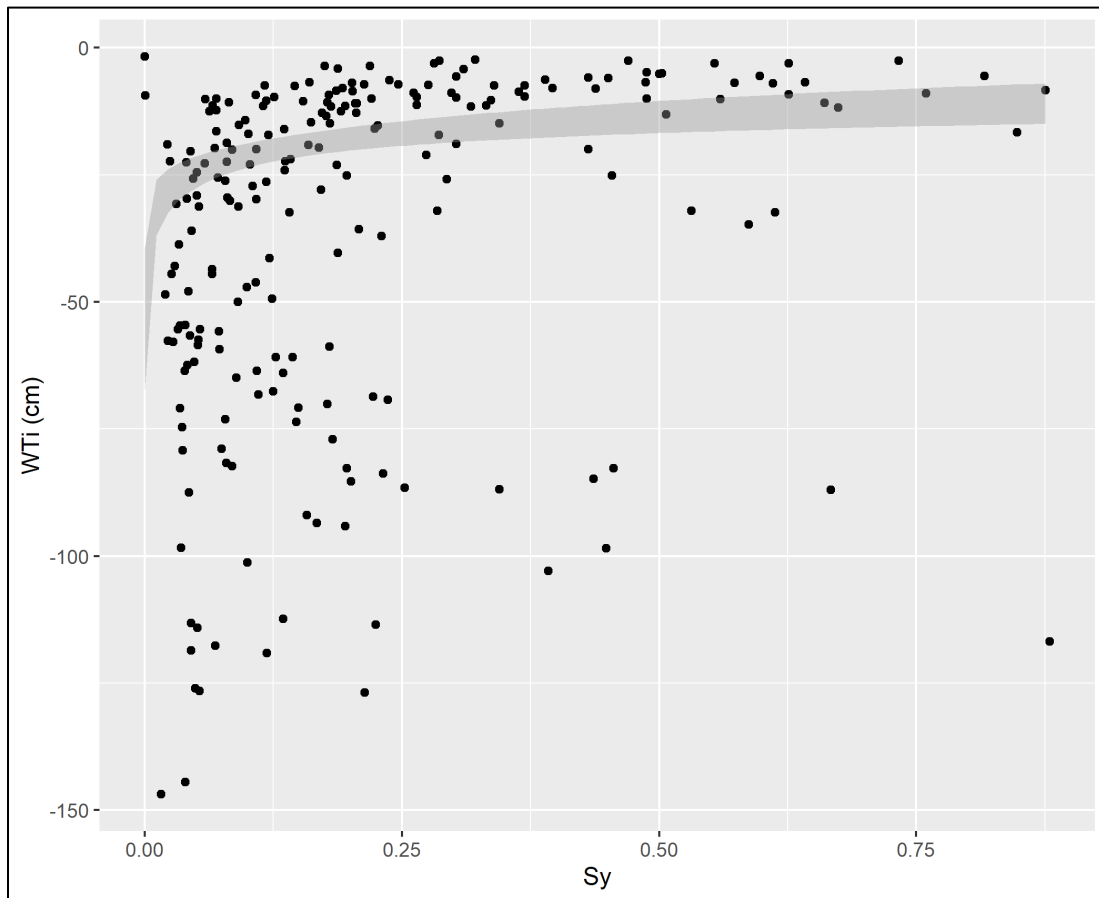


Figure 4.13  $\Delta WTs$  and  $S_y$  as a function of % sedge cover class. The asterisks above each of the bars represents the level of significance between each pair. The fewer the asterisks, the closer the  $p$  value is to 0.05.



### 4.3 Specific Yield

As calculated from  $P_i$ , the median  $S_y$  was 0.160 with a maximum of 0.880 and a minimum of 0.0001 (Figure 4.14). The bootstrapped  $S_y$  distribution had a median of 0.158 and lower and upper 95% confidence intervals of 0.127 and 0.183, respectively (Figure 4.15). A plot of  $\Delta WT$  as a function of rainfall with lines of equal  $S_y$  overlaid shows that larger  $S_y$  values are generally associated with larger rainstorms and smaller water table fluctuations (Figure 4.16).



*Figure 4.14 Relationship between  $S_y$  and  $WT_i$ . The dark grey range indicates the 95% confidence interval for the data between 0 and -50 cm depth.*

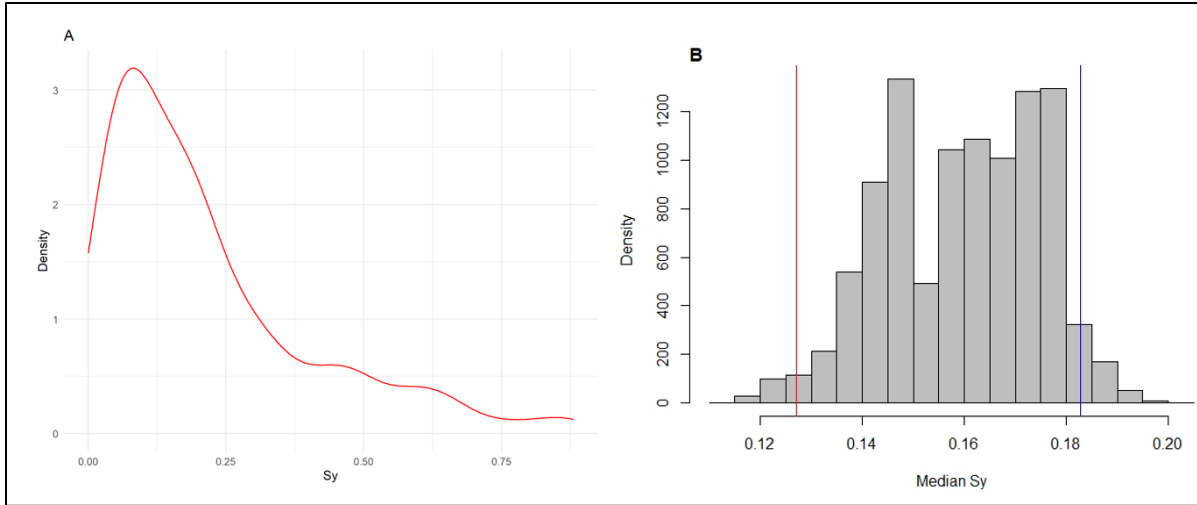


Figure 4.15 Density distribution of  $S_y$  (A) and bootstrapped  $S_y$  (B). In B, the red and blue lines represent the lower and upper 95th percentiles, respectively.

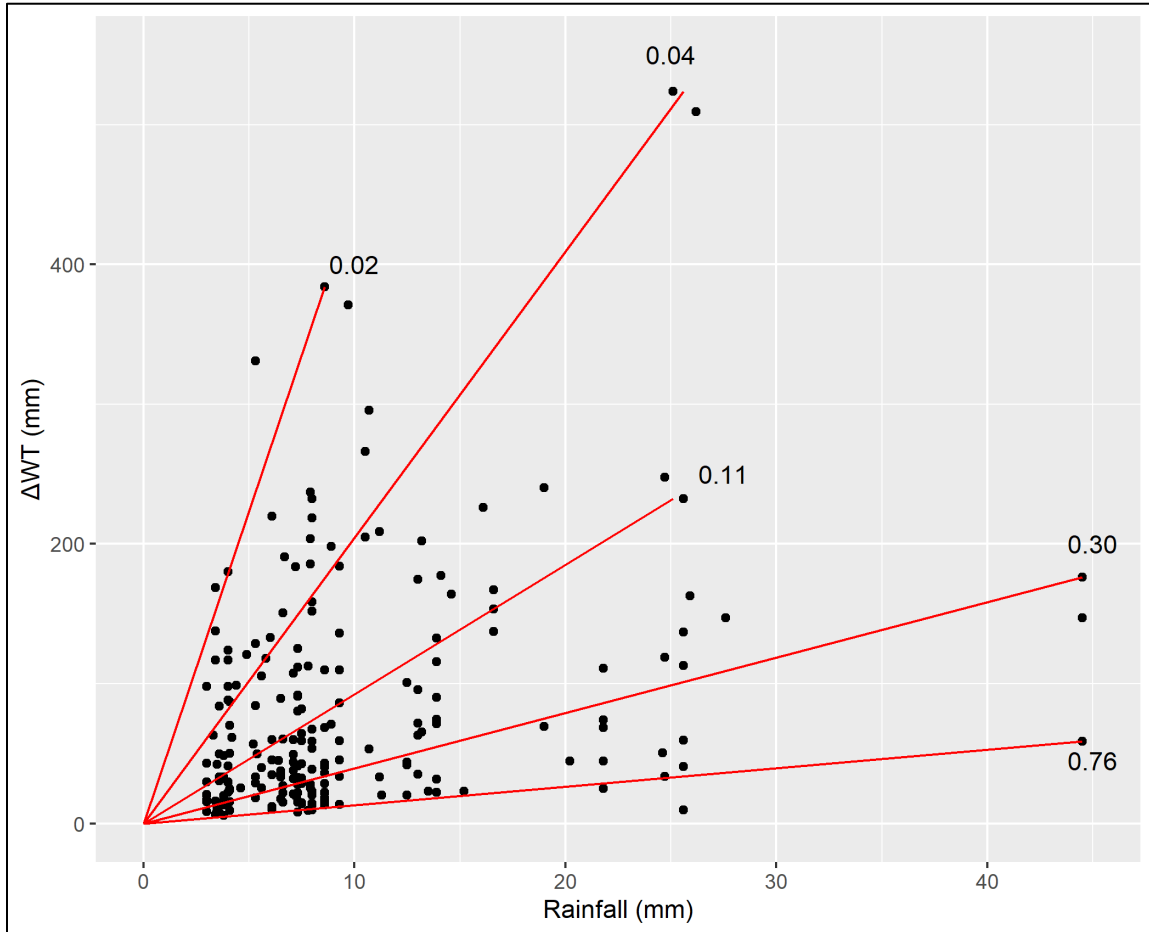


Figure 4.16 Water table variation as a function of rainfall size (points). The red lines and their value indicate  $S_y$ .

#### 4.4 Spatial and Seasonal Variability of Specific Yield

$S_y$  declined non-linearly between the peat surface and -50 cm (Figure 4.14). The equation best representing this decline is  $\ln(S_y) = ((WT_i) + 11.172) / 3.367$ ,  $R^2 = 0.11$  (Figure 4.14). Between -50 and -110 cm,  $S_y$  values and their variability increased (Figure 4.14).

$S_y$  varied across the fen,  $\chi^2 = 51.28$ ,  $p < 0.001$  (Figure 4.17). The well site with the highest median  $S_y$  was W19 (0.39), while the well site with the lowest median  $S_y$  was W60A (0.05) (Appendix B). Median  $S_y$  for all other well sites fell between 0.07 and 0.28 (Appendix B). W44 had the largest range in  $S_y$ , while W11 had the smallest range (Appendix B). Kriged values showed a spatial relationship between the location of alluvial fans (Figure 3.1) and higher  $S_y$  values (Figure 4.18).

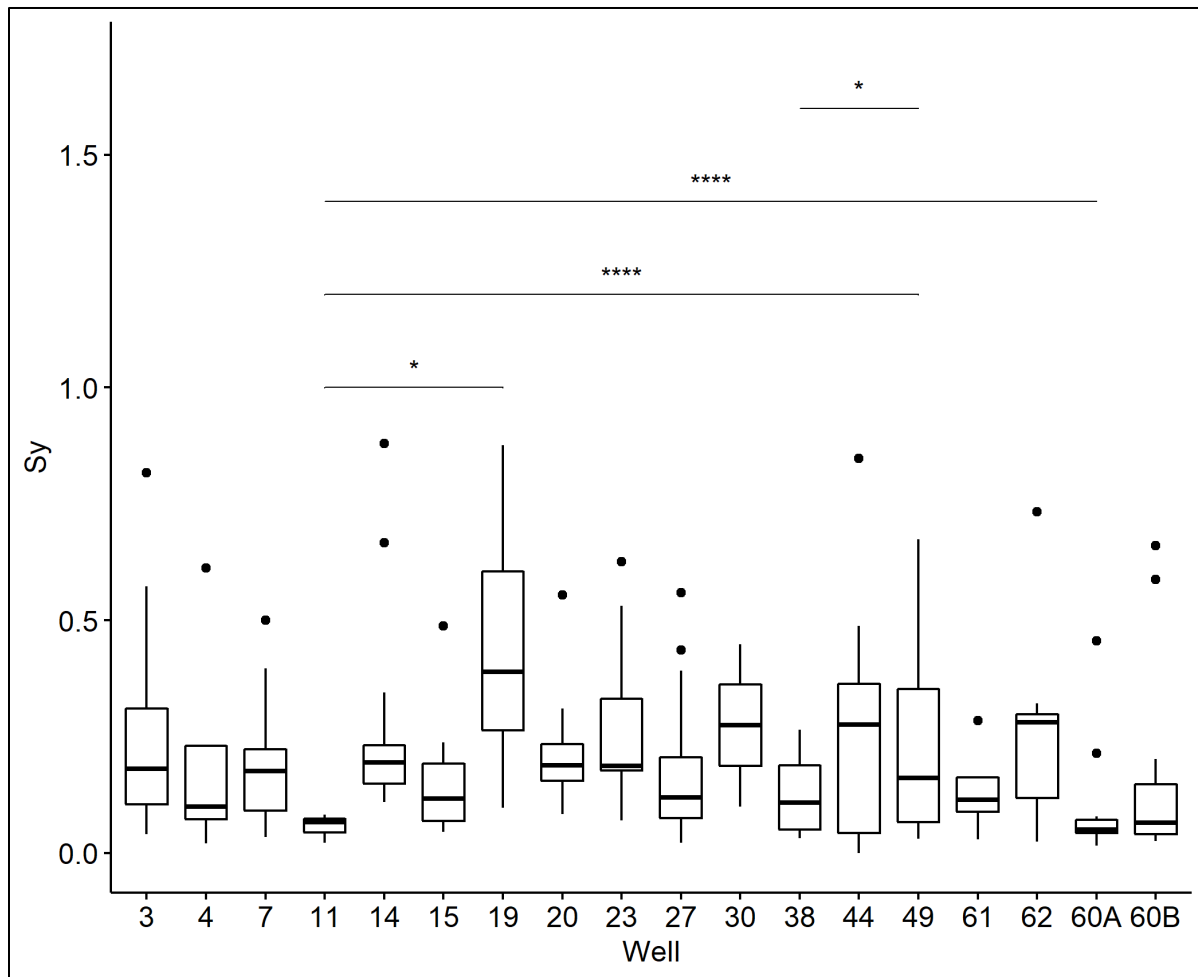
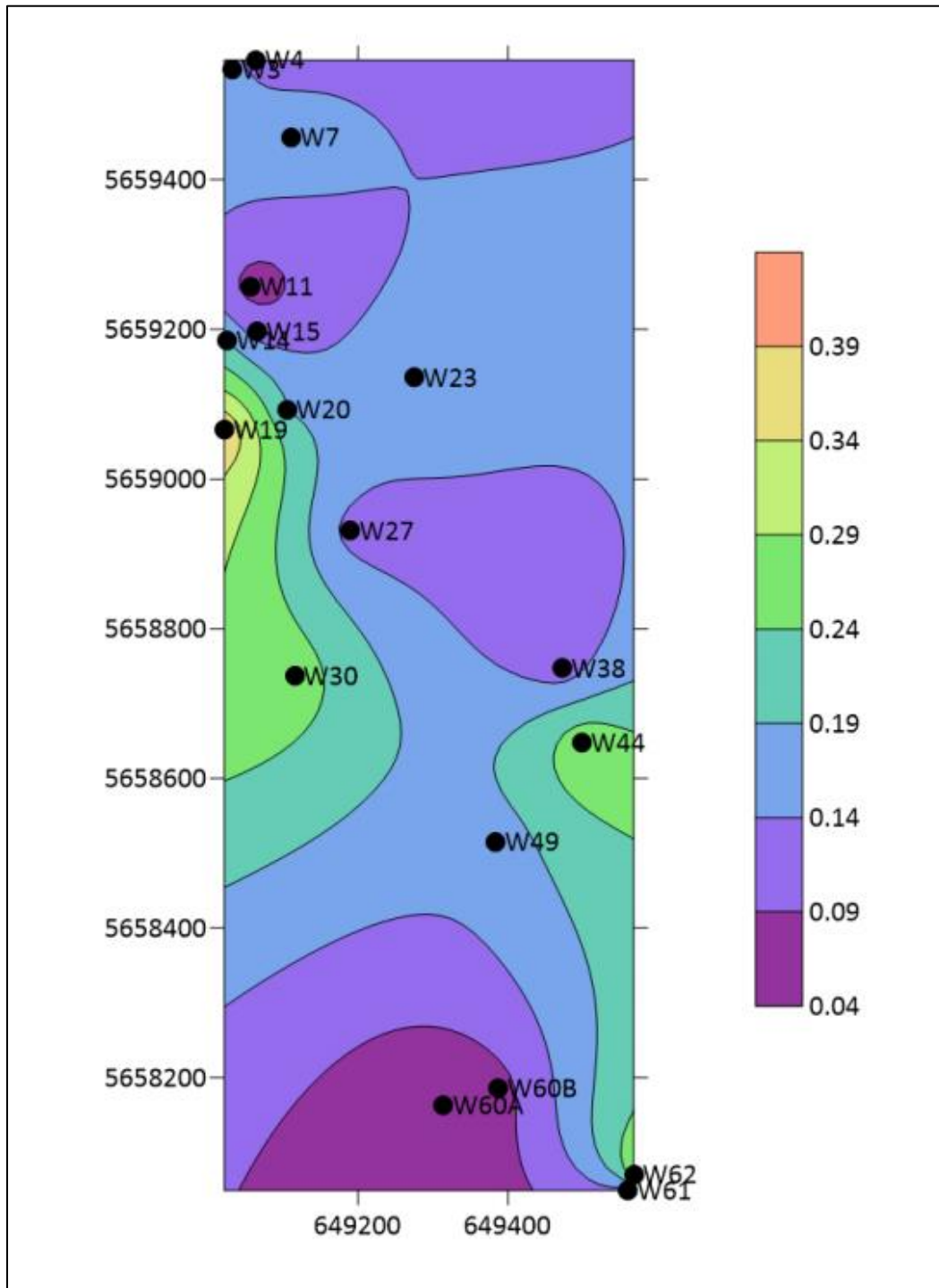


Figure 4.17 Range of  $S_y$  values categorized by well. The asterisks above each of the bars represents the level of significance between each pair. The fewer the asterisks, the closer the  $p$  value is to 0.05.

Median  $S_y$  was similar for May-June (0.195) and July-August (0.176) and significantly higher than in September (0.094),  $z$ -score = 6.75,  $p$  = 0.034 (Figure 4.10C).



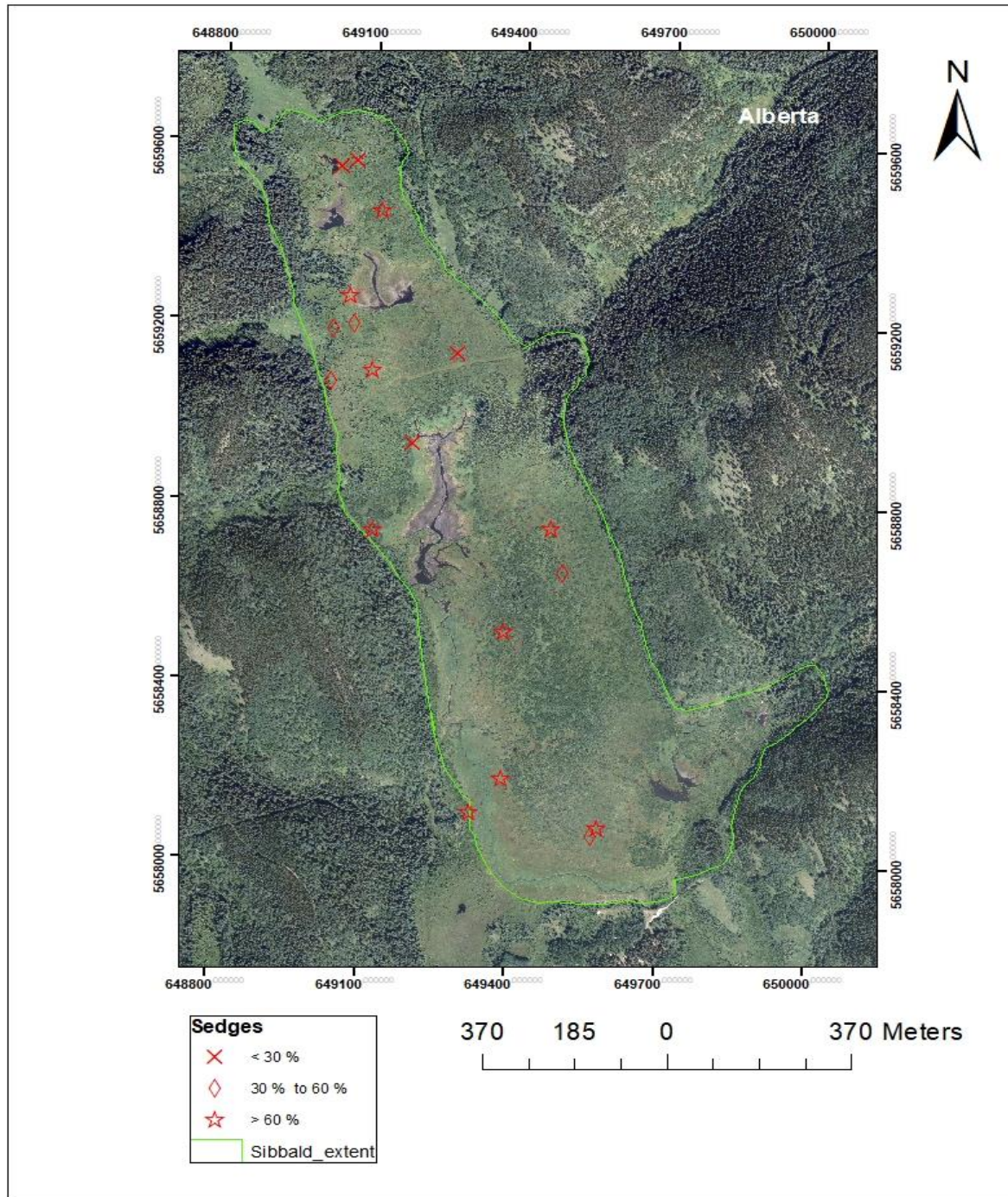
*Figure 4.18 Map showing kriged  $S_y$  at Sibbald Fen with the fen cropped into a rectangular domain.*

$S_y$  values were significantly different between all years studied,  $z$  score = 22.7,  $p = 0.0019$  (Figure 4.11C). The largest ranges of  $S_y$  occurred in 2008 (0.81), 2009 (0.88), and 2020 (0.70), while the smallest range occurred in 2015 (0.02) (Figure 4.11C).

#### **4.5 Factors Regulating Specific Yield**

$S_y$  differed among soil profiles,  $z$ -score = 16.5,  $p = 0.000261$  (Figure 4.12B). PMG soil profiles had larger  $S_y$ , and PMP soil profiles had smaller  $S_y$  (Figure 4.12B).

The distribution of % sedge cover for each of the studied wells can be seen in Figure 4.19. Spatial patterns of % sedge cover show that sedges are the dominant vegetation in the southern half of the fen and become less dominant as you move north. There was no relationship between  $S_y$  and % sedge cover class ( $z$ -score = 0.039,  $p = 0.981$ ) (Figure 4.13B).



*Figure 4.19 Visualization of % sedge cover at each well studied at Sibbald Fen.*

## 5. DISCUSSION

Water storage capacity was studied via the water table fluctuation method for a peatland, Sibbald Fen, located in the Canadian Rocky Mountains. The median  $S_y$  for Sibbald Fen was 0.158 (95% CI of [0.127, 0.183]). Various factors that might influence  $S_y$ , including water table depth, soil profile complexity, % sedge cover and seasonality, were studied. The hypothesis tested in this study was supported for the factors of depth, soil profile complexity and seasonality. There was high variability in  $S_y$  at shallow depths with decreasing  $S_y$  and increased variability between -50 and -110 cm depth. The highest  $S_y$  was associated with the peat-mineral-gravel soil profile, while the lowest  $S_y$  was in the peat-mineral-peat soil profile.  $S_y$  and  $\Delta W T_s$  were similar across % sedge cover classes. Time within the growing season and year influenced  $S_y$  and  $\Delta W T_s$  owing to differences in the location of the water table relative to the ground surface. September was statistically different from May-August and was characterized by low  $S_y$  values and large  $\Delta W T_s$  brought about by deep water tables. On a year-to-year basis, the change in overall wetness (the number of rainfall events) was the controlling factor of water table position, impacting both  $S_y$  and  $\Delta W T_s$ . These results suggest that the complexity of mountain peatlands is a crucial factor in determining peatland  $S_y$ .

### 5.1 Specific Yield and Depth

The relationship between depth and  $S_y$  has been identified as important in many peatland studies (e.g., Price, 1996; Carlson-Mazur et al., 2013; Bourgault et al., 2016, 2018). However, the depth- $S_y$  relationship found in this study is very different from that reported by other studies, likely due to the studied peatland's physiographic setting. In this study, there is a large range of  $S_y$  at shallow depths (Appendix C). This abundance of data at shallow depths is due to the water table primarily being near the ground surface for the first half of the growing season, leading to a greater number of data points. The range of  $S_y$  seen between 0 and -50 cm depth in this study is similar to ranges found in other studies (Price, 1992, Bourgault et al., 2016, & Bourgault et al., 2018).  $S_y$  is relatively high near the peat surface because of high porosity (Rezanezhad et al., 2016). Overall (0 to -150 cm depth), the range of  $S_y$  found in this study (0.0001 to 0.88) agree with those of Price (1992; 0.1 to 0.5), Carlson-Mazur et al. (2013; 0.05 to 0.45), and Bourgault et al. (2016 & 2018; 0.13 to 0.99 and 0.01 to 0.95, respectively). Price (1996) found that  $S_y$  decreased linearly at the impacted site and semi-linearly at the natural site until 65 cm depth.

Carlson-Mazur et al. (2013) reported a linear decrease in  $S_y$  to 3 m depth, whereas Bourgault et al. (2016 & 2018) reported a logarithmic decrease in  $S_y$  until 1m depth. Duval & Waddington (2018) found one well location which followed a pattern similar to the  $S_y$  increase at depth observed in this study. However, they did not state a cause for the increase in  $S_y$  at depth.  $S_y$  at Sibbald Fen increases between -50 to -110 cm, and variability increases at this depth to what was estimated in the upper 50 cm of peat. That said, an increase in  $S_y$  and its variability at depth was only seen at a few of the well sites (i.e., 14, 27, 30 and 60A).

The  $S_y$  increase found with depth at Sibbald is likely due to the changes in substrate within the soil profile. In contrast to the other literature where  $S_y$  of Canadian peatlands has been studied (i.e., Price, 1992 – southeastern Newfoundland, Price, 1996 – southern Ontario, Carlson-Mazur et al., 2013 – northeastern Michigan, Bourgault et al., 2016 & 2018 – southern Quebec), mountain environments are active geomorphologically, which can lead to layers of mineral sediment interbedded within the peat (Cooper et al., 2012; Wang et al., 2016). Depth variation in substrate causes a change in hydraulic properties such as hydraulic conductivity and porosity. The interbedding of mineral layers in the peat significantly affected the response of the water table to precipitation inputs and thus the calculated  $S_y$ . At wells 14 and 60A, the soil profile follows a peat-mineral-gravel pattern where the shift from peat to mineral sediment occurs at approximately 50 cm depth – owing to the sudden increase in  $S_y$  at these two wells. However, at wells 27 and 30, the sudden increase in  $S_y$  values occurs within the peat layer closest to the ground surface.

It is hypothesized that the  $S_y$  spike in wells 27 and 30 at depth is due to a shift in hydraulic properties brought about by compaction, change from sedge to moss peat, or a combination of both. Dettman & Bechtold (2016) and Wong et al. (2009) examined peat compaction. The compaction and expansion of peat brought about by changes in the water table are known as mire breathing (Ingram, 1983 in Price & Schlotzhauer, 1999). Mire breathing impacts  $S_y$  by causing the porosity of peat to be dynamic over time. As mire breathing occurs, the water table reacts differently to precipitation events causing changes in  $S_y$ . Two types of compaction affect the storage capacity of peatlands: (1) normal compression, where the change in peat volume is equal to the volume of water lost and (2) residual shrinkage, where compression is due to air entering the soil pores (Price & Schlotzhauer, 1999). Price and



Schlotzhauer (1999) state that the changes in peat volume are greater for normal compression than it is for residual shrinkage, and so the uncertainty in  $S_y$  introduced by mire breathing should be small. The impact of normal compression of the peat described by Price and Schlotzhauer (1999) will likely be applicable to the PP peat profiles but not the PMP and PMG peat profiles at Sibbald Fen. Less shrinkage and compression are likely occurring in the mineral sediment present in PMP and PMG wells, as the compressibility of gravel is negligible, and sand has a low compressibility (Price & Schlotzhauer, 1999). Compression is different for mineral sediment than peat soil due to the size and shape of the soil particles. It is recommended that the changes in peat volume brought about by changes in the water table be studied for peatlands in mountain regions where the soil profile is not homogeneous as it is likely an important factor in determining  $S_y$ .

Unlike the other wells where an increase in  $S_y$  was experienced with depth, well 38 is located in a PP soil profile. The cause for well 38 experiencing an increase in  $S_y$  with increasing depth could potentially be due to the shift from sedge to moss peat at depth. The type of peat present determines its physical properties (Boelter, 1968). A change in hydraulic properties with a shift in peat type is brought about by the decomposition rates of each type of peat – an example being that moss peat typically has a lower hydraulic conductivity than sedge peat due to slowed decomposition under saturated conditions (Crockett et al., 2016). At Sibbald Fen, surface peat is typically sedge peat, while at depth, it is usually moss peat (Wang et al., 2016). Given that the water table drops occasionally drops into the moss peat, and likely will do so more often under climate change (Streich & Westbrook, 2020), future studies should explore how  $S_y$  is influenced by peat type in mountain fens

Counter to expectations, the percentage of sedge coverage at the surface near each well did not explain the  $S_y$ -depth relationship found in PP soil profiles. The lack of a relationship between percent sedge cover and  $S_y$  is likely due to the simple nature of the vegetation data. While the type of vegetation present at the ground surface partially dictates the type of peat formed, only capturing the % of sedge cover class at one quadrat for each well does not provide an in-depth analysis of the types of vegetation involved in peat formation. Future studies may want to consider a more robust research design that includes a detailed analysis of vegetation present at each well site and determination of the spatial correlation between vegetation, type of peat present, peat degree of decomposition, and the thickness of each type of peat.

## 5.2 Spatial Specific Yield

There is some spatial consistency among the  $S_y$  values found at each well. Most wells (3, 4, 7, 14, 15, 20, 23, 27, 30, 44, 60B, 61, and 62) had  $S_y$  medians similar to one another. Only wells 11, 19, 38, 49, and 60A were statistically different from the others. The statistical difference between wells 11, 19, 38, 49 and 60A are likely due to the changes in hydraulic properties with depth at each well – specifically porosity and hydraulic conductivity. These wells differ from other PMP and PMG wells due to the proximity to alluvial fans, causing more coarse mineral sediment to be present. The soil profile at Sibbald Fen is not homogeneous - the soil profile includes interspersed mineral sediment layers. In the kriged  $S_y$  results, a spatial relationship was found to exist between where alluvial fans intersected the peatland margin and corresponded to areas with high  $S_y$  along the western edge of the peatland. This relationship also coincides with the location of PMG wells where the gravel layer intersected was likely the buried alluvial fans. The interaction of these relationships helps to demonstrate the impact that changes in the soil profile have on the hydraulic properties (specifically hydraulic conductivity and porosity) which influence  $S_y$ . The relationship between porosity and hydraulic conductivity is that the higher the porosity and the larger the pores, the greater hydraulic conductivity will be (Dingman, 2015) and the more it will affect  $S_y$ . As demonstrated by Bourgault et al. (2018),  $S_y$  and hydraulic conductivity are often correlated – as hydraulic conductivity increases, so does  $S_y$  (Bourgault et al., 2018, Figure. 15). A relationship between  $S_y$  and hydraulic conductivity thus dictates that as depth within a PMP soil profile increases and a clay-dominated mineral layer is intersected, the  $S_y$  can be expected to decrease. When the opposite is true,  $S_y$  will increase, as is the case within a PMG soil profile. It is important to note that peat has moderate to high hydraulic conductivity depending on the degree of humification and compaction (Wong et al., 2009). Janzen & Westbrook (2011) report hydraulic conductivity values for Sibbald Fen, ranging between  $10^{-3}$  and  $10^{-6}$  at 0 to -50 cm depth and between  $10^{-5}$  and  $10^{-8}$  at -50 to -140 cm depth. From these values, using the relationship found by Bourgault et al. (2018),  $S_y$  is then expected to be greater between 0 and -50 cm depth and decline with depth to -140 cm. However, the relationship (described by Bourgault et al. (2018)) only applies to purely peat profiles. Thus, the relationship between  $S_y$  and hydraulic conductivity will change as mineral sediments are encountered with depth at Sibbald Fen. Examples of this mineral sediment intersection occur in

wells 11, 19, 49 and 60A, where PMG and PMP soil profiles include these mineral sediment layers and an increase in  $S_y$  is found.

Overall, the spatial variability of  $S_y$  is likely to vary from peatland to peatland – especially in mountain settings where there is a high degree of variability in the soil profile (Morrison et al., 2015). While many peatlands in mountain regions are rich in sedges (Cooper et al., 2012), the active geomorphology brings about the variability of the soil profile. Geomorphological features encroaching on mountain peatlands can include active alluvial fans, avalanche paths, tephra deposits from volcanic eruptions, glacial features (moraines, till plains, etc.), and in some cases, impacts by beaver (Morrison et al., 2015). The presence of these features creates settings that promote episodic periods of deposition of mineral sediments interrupting periods of prolonged peat accumulation, resulting in complex peatland soil profiles.

### **5.3 Temporal Specific Yield**

$S_y$  was also affected by seasonality – both during the growing season and inter-annually – via its influence on the position of the water table. Typical of mountain peatlands, the water table at Sibbald Fen is generally closer to the ground surface early in the growing season when the ground is still frozen. The peat at Sibbald Fen can stay frozen into July (Streich & Westbrook, 2020). Ground frost reduces the space available for water storage (i.e., effective porosity), impacting the water table position (Guan et al., 2010) and thus  $S_y$ . The presence of ground frost or ice lenses within peat reduces downward infiltration and causes water tables to remain closer to the ground surface, leading to water tables at or above the ground surface as precipitation events and snowpack melt cause the water table to rise (Guan et al., 2010). There is added variability in water table depth concerning the frost surface at Sibbald Fen, as the frost table has been shown to thaw heterogeneously (Streich & Westbrook, 2020). High water tables (brought about by winter snowmelt and frost thaw) combined with low evapotranspiration early in the growing season means more water is available within the soil profile, leading to higher  $S_y$  (Price & Schlotzhauer, 1999; Carlson-Mazur et al., 2013). The opposite is true later in the growing season when water tables have declined due to increased evapotranspiration and reductions in rainfall events (Price & Schlotzhauer, 1999; Carlson-Mazur et al., 2013).

A decline in the water table can also lead to compression of the peat and thus a reduction in  $S_y$ . It was shown that  $S_y$ ,  $WT_i$ , and  $\Delta WT$  in September were statistically different from May-

August, indicating that something occurs in September, causing it to be different. The most likely explanation for this difference is that combining deeper water tables and large  $\Delta W_T$  led to low  $S_y$  values in September. It is hypothesized that compression throughout the growing season could also cause the decrease seen in  $S_y$ . Though not examined in this study, the relationship between evapotranspiration rates and time within the growing season also impacts the  $S_y$  at Sibbald Fen (Streich & Westbrook, 2020). As evapotranspiration demands increase, more water is removed from groundwater resources causing the water table to drop. This drop in the water table then causes a reduction in  $S_y$ . Due to the time-varying nature of  $S_y$  at Sibbald Fen, it is recommended that when modelling, parameters be included that represent the decline of the water table over time and how the soil profile changes across the depth of the water table decline. Another recommendation is that the bootstrapped confidence interval values be used to determine the uncertainty of water storage capacity when a single specific yield value is being used to represent an entire peatland in a watershed or regional hydrological model.

$S_y$  also varied inter-annually. Years with shallower water tables coincided with years that had more overall precipitation. Wet and dry conditions affect the physical response of the water table to precipitation inputs. In wetter years (2008, 2009, 2018, 2019, & 2020), the water table was shallower, and in drier years (2014, 2015, and 2017), the water table was deeper. When the water table was closer to the ground surface, the water table response to precipitation events was greater, leading to higher  $S_y$  and vice versa in dry years. Thus, the climate conditions play a major role in determining where the water table is located. When the water table is located near the ground surface, as is the case in wetter years, the water table fluctuations being measured are located within the peat portion of the profile. This will impact the specific yield that is calculated due to the hydraulic properties of peat. However, during drier years the location of the water table is deeper, this leads to specific yield being calculated for either mineral sediments or deeper peat - both of which have very different hydraulic properties compared to shallow peat. The interaction between the water table and deeper mineral/peat material is discussed further in section 5.1 though this relationship will still need to be studied further. The dryness of 2014 and 2015 was enhanced by the 2013 flood experienced in Alberta, which caused several large beaver dams at Sibbald Fen to breach (Westbrook et al., 2020) and the water table to decline (Karran et al., 2018). These deeper water tables lead to  $S_y$  being measured within the mineral sediment layers, and/or the deeper, more compressed peat.

The difference in  $S_y$  between wet and dry years directly influences the water volume released by the fen to the stream. For example, by considering the lower and upper 95<sup>th</sup>  $S_y$  percentiles, a water table drop of 40 cm across the whole peatland results in water loss of between  $4.17 \times 10^3 \text{ m}^3$  and  $9.25 \times 10^4 \text{ m}^3$ , while a water table drop of 60 cm results in water loss of between  $9.39 \times 10^3 \text{ m}^3$  and  $1.43 \times 10^5 \text{ m}^3$ . These water table declines are characteristic of average conditions at Sibbald Fen. During a dry year, as much as  $3.9 \times 10^4 \text{ m}^3$  of water flows out of Bateman Creek from May 1<sup>st</sup> through September 30<sup>th</sup> based on the streamflow measurements of Streich & Westbrook (2020). The magnitude with which water is lost from Sibbald Fen due to a decline in the water table is nearly equivalent to that lost due to streamflow. This indicates the release of water from the fen is critical in maintaining baseflow in Bateman Creek.

#### **5.4 Factors Regulating Specific Yield**

Another thing to consider is the impact of changing climates on the factors examined in this study, specifically the location of the water table as the water table declines experienced are expected to become more extreme. This has implications for the magnitude of water loss from a peatland. The depth range of the water table is regulated by the amount of snowmelt, thawing of the frost table, and the amount of precipitation received throughout the growing season (Drexler et al., 2013; Streich & Westbrook, 2020). As the climate warms, peatlands throughout Canada are expected to experience a much greater seasonal decline in water tables than is currently observed (Price & Schlotzhauer, 1999; Whittington & Price, 2006; Drexler et al., 2013, Cobb & Harvey, 2019; Cooper et al., 2019; Ahmad et al., 2021). A decline in the water table is then expected to cause an increase in peat decomposition and compression – which then leads peatlands to act as carbon sources rather than carbon sinks (Price & Schlotzhauer, 1999; Whittington & Price, 2006; Millar et al., 2017). Peatlands have been shown to self-regulate to maintain their water tables (Waddington et al., 2015); however, this research was conducted in a peatland with a continuous peat profile and thus there is the potential for the presence of mineral sediment to interfere with this self-regulation in mountain peatlands.

The results presented herein show that the long-term observation of water table can be invaluable in providing insight into fen water storage and release. The results also indicate the need for further research to examine the impacts of climate change on water storage and release. There is uncertainty associated with factors not included in the calculation of  $S_y$ , such as

evapotranspiration, which has been shown to strongly impact peat hydrologic properties in other studies (e.g., Chason & Siegel, 1986; Crosbie et al., 2005; Gribovszki, 2018; Valios et al., 2020). This can be addressed by collecting additional data that impacts the calculation of  $S_y$ , namely evapotranspiration, hydraulic conductivity, and porosity. There is a small degree of uncertainty associated with the water table fluctuation method as it relies on frequent and precise measurements of changes in the water table. For example, some years of the data used in this study was collected in 15-minute intervals, while other years had data collected in hourly timesteps. Based on a simple comparison analysis, this difference in measurement intervals causes a 1-5% difference in  $S_y$  estimate accuracy when the water table data is collected in 15-minute vs. hourly intervals. It is recommended that a protocol for water table data collection be established to address this. See section 6.2 for further details. There is also added uncertainty in the measurements of the water table as there is the potential for levelogger malfunction and the water table to drop below the logger sensor. To ensure loggers are functioning correctly and data is being recorded it is important to perform regular field data checks.

## **6. CONCLUSION**

This study aimed to examine water storage capacity for a mountain peatland and the factors affecting it. This was achieved by testing the hypothesis that specific yield will not be depth-dependent, as is the case for peatlands with continuous peat soil profiles, owing to spatial variations in interbedding of mineral materials in the peat matrix. After applying the bootstrap method to calculations of specific yield attained via the water table fluctuation method, median specific yield for Sibbald Fen was 0.158 with an upper and lower 95% CI of 0.127 and 0.183, respectively. Specific yield was variable, with the highest median value associated with W19 at 0.39 and the lowest value associated with W60A at 0.05. Analysis of specific yield by depth showed that vertical heterogeneity of the soil profile in mountain settings is crucial. A logarithmic relationship described changes in specific yield with depth, but only until approximately -50 cm depth. Beyond that, specific yield and its variability increased until -110 cm depth. It is now known that these increases in specific yield are associated with changes in the substrate and their hydraulic properties. The spatial and temporal analysis of specific yield demonstrated that location within the peatland and seasonality play an essential role in determining specific yield. The spatial variability of specific yield was controlled by the type of soil profile each well was located within. Wells in the PMG soil profile category had higher specific yield values, while PMP soil profiles had smaller specific yield values. The seasonality analysis showed that the location of the water table was the factor influencing specific yield over time. September was found to have the lowest specific yield compared to the rest of the growing season (May-August) due to deep water tables. Years that received more precipitation also had larger specific yields than drier years and water tables closer to or at the ground surface.

### **6.1 Implications**

This research has implications for applying the water table fluctuation method to calculate specific yield in mountain peatlands. To develop a comprehensive understanding of the variability of specific yield in mountain peatlands, the dynamic characteristics of the site must be known. These characteristics include the heterogeneity of the soil profile regarding substrate and hydraulic properties with depth, the changes experienced spatially within the peatland, and the changes experienced over time. The hydraulic properties which change with depth in a mountain peatland are the hydraulic conductivity, porosity, compressibility, type of peat, degree of

decomposition, and bulk density (e.g., Chason & Siegel, 1986; Hogan, 2006; Bourgault et al., 2018), all of which impact specific yield. Spatially and temporally, the location of the water table impacts specific yield. Early in the growing season, the water table is closer to the ground surface due to the melting of the winter snowpack and increased precipitation. This contrasts the drier conditions later in the growing season which lead to deeper water tables. Inter-annually, the location of the water table is impacted by the overall wetness and antecedent moisture conditions. Because the water table fluctuation method does not consider these additional factors impacting specific yield, additional work must be done to understand the variability seen in mountain peatlands. Another reason to develop a better understanding of mountain peatland variability is climate change. As the climate warms, water tables are expected to decline (Cobb & Harvey, 2019; Cooper et al., 2019; Ahmad et al., 2021) to levels much lower than what is currently seen throughout the growing season. As the peat dries and begins to compress the hydraulic properties of the peat will shift – porosity and hydraulic conductivity will decrease (Price & Schlotzhauer, 1999; Ahmad et al., 2021). This will then impact the ability of the peatland to store and release water, affecting the role of valley-bottom peatlands to supply low streamflows and attenuate high flows.

## **6.2 Limitations**

There are several limitations identified regarding this research. The first limitation is that hydraulic conductivity and porosity were not measured. The type of peat and degree of peat humification were also not examined. The importance of hydraulic conductivity and porosity is that they directly impact specific yield by controlling how much water the peat can store and how easily it will retain that water under the force of gravity. The type of peat and humification impact specific yield by directly impacting porosity and hydraulic conductivity (Crockett et al., 2016). Studying these hydraulic and peat properties could provide further insight into the spatial and temporal variability of specific yield and the magnitude of water table changes at different water table positions.

Another limitation is that the method by which percent sedge cover was examined is simple. This limitation is important since the type of peat is controlled by the type of vegetation actively growing within the peatland. This limitation could be mitigated by capturing a more in-depth analysis of the types of vegetation growing throughout the fen by someone with more in-



depth vegetation knowledge. This knowledge would allow for a better understanding of the relationship between peat-forming vegetation and specific yield.

A third limitation is not knowing the contribution of groundwater to the fen. By not knowing the contribution of groundwater to the fen, all water table changes are assumed to be results of rainfall events. At Sibbald Fen, the results of Streich & Westbrook (2020) show that groundwater does contribute to the fen, even during extreme drought years. However, the estimates of groundwater were derived from residuals from the water balance approach and thus contains large amounts of uncertainty and potential error. To mitigate this, a study which examines the impact of groundwater contributions from both to and from the alluvial aquifer as well as from the adjacent hillslopes would provide insight into the water storage and release at Sibbald Fen.

The fourth limitation is that a historical dataset was used. The dataset was collected to meet the needs of other research projects, and thus was not collected with this type of analysis in mind. There is high value in obtaining long-term records of water table in mountain peatlands, including to understand how climate change will influence their ability to store and release water. The datasets used varied in their data collection frequency, spatial distribution and temporal distribution change from one year to the next. Not all wells had data collected across the entire study period, and thus there are limitations to developing a spatial understanding of specific yield across the fen and with depth. By only collecting data for a specific set of wells over a short period, spatial analysis is confined to that period. In the future, I recommend that there be a standardized well data collection procedure wherein the same wells are monitored throughout the same dates and a timestep of 15 minutes or less be used to consistently record changes in the location of the water table.

### **6.3 Recommendations**

There are several recommendations following the completion of this research. Suggestions for future research include examining the way(s) in which beavers impact the hydraulic properties and location of the water table in mountain fens as the two often go hand in hand (Morrison et al., 2015). We know that beavers are capable of altering the hydrology of mountain peatlands (Karran et al., 2018), and by developing an understanding of how they affect the location of the water table, we will better understand the long-term sustainability of these

unique ecosystems. Another suggestion for future research is examining how peatlands adjacent to rivers and streams sustain low flows as the spatial and temporal variability of available water resources is high. Since peatlands in mountain regions can be heavily impacted by climate changes (section 2.4), understanding how the hydrology of mountain peatlands will change under the stress of a shifting climate is critical. It is understood that as climate changes, peatlands are expected to shift from a carbon sink to a carbon source as water tables decline, and peat is no longer near or at saturated conditions (Millar et al., 2017). Therefore, another potential research focus will be to understand better how peatland degradation brought on by changes in peatland carbon storage will impact the peatlands' ability to store and release water as the water table fluctuates.

## 7. REFERENCES

- Ahmad, S., Liu, H., Alam, S., Gunther, A., Jurasinski, G., & Lennartz, B. (2021). Meteorological Controls on Water Table Dynamics in Fen Peatlands Depend on Management Regimes. *Fronteris in Earth Science*, 9(March), 1-13.
- Aldous, A. R., Gannett, M. W., Keith, M., & O'Connor, J. (2015). Geologic and Geomorphic Controls on the Occurrence of Fens in the Oregon Cascades and Implications for Vulnerability and Conservation. *Wetlands*, 35(4), 757–767. <https://doi.org/10.1007/s13157-015-0667-x>
- Boelter, D. (1968). Important Physical Properties of Peat Material. *Third International Peat Congress*, 150-155.
- Bourgault, M. A., Larocque, M., & Roy, M. (2014). Simulation of aquifer-peatland-river interactions under climate change. *Hydrology Research*, 45(3), 425–440. <https://doi.org/10.2166/nh.2013.228>
- Bourgault, M. A., Laroque, M., & Garneau, M. (2016). Quantification of peatland water storage capacity using the water table fluctuation method. *Hydrological Processes*, 31(5), 1184-1195.
- Bourgault, M. A., Laroque, M., Garneau, M., & Roux, M. (2018). Quantifying peat hydrodynamic properties and their influence on water table depths in peatlands of southern Quebec (Canada). *Ecohydrology*, 11(7), 1-12.
- Bourgault, M. A., Larocque, M., & Garneau, M. (2019). How do hydrogeological setting and meteorological conditions influence water table depth and fluctuations in ombrotrophic peatlands? *Journal of Hydrology*, 4, 1-14.
- Britannica, The Editors of Encyclopaedia. "Stratigraphy." *Encyclopedia Britannica*, 19 Jan. 2021, <https://www.britannica.com/science/stratigraphy-geology>. Accessed 28 July 2021.
- Bullock, A., & Acreman, M. (2003). The role of wetlands in the hydrological cycle. *Hydrology and Earth System Sciences*, 7(3), 358–389.
- Buttle, J. (2006). Mapping the first-order controls on streamflow from drainage basins: the T<sup>3</sup> template. *Hydrological Processes*, 20, 3415-3422.
- Carlson-Mazur, M. L., Wiley, M. J., & Wilcox, D. A. (2013). Estimating evapotranspiration and groundwater flow from water-table fluctuations for a general wetland scenario. *Ecohydrology*, 7(2), 378-390.
- Chason, D. B. & Siegel, D. I. (1986). Hydraulic conductivity and related physical properties of peat, Lost River Peatland, Northern Minnesota. *Soil Science*, 142(2), 91-99.
- Chimner, R. A., Lemly, J. M., & Cooper, D. J. (2010). Mountain fen distribution, types and

- restoration priorities, San Juan Mountains, Colorado, USA. *Wetlands*, 30(2), 763–771. <https://doi.org/10.1007/s13157-010-0039-5>
- Cobb, A. R., & Harvey, C. F. (2019). Scalar Simulation and Parameterization of Water Table Dynamics in Tropical Peatlands. *Water Resources Research*, 55(11), 9351–9377.
- Cooper, D. J., Chimner, R. A., & Merritt, D. M. (2012). Western Mountain Wetlands. In *Wetland Habitats of North America: Ecology and Conservation Concerns* (pp. 313–328).
- Cooper, D. J., Sueltenfuss, J., Oyague, E., Yager, K., Slayback, D., Caballero, E. M. C., ... Mark, B. G. (2019). Drivers of peatland water table dynamics in the central Andes, Bolivia and Peru. *Hydrological Processes*, 33(13), 1913–1925. <https://doi.org/10.1002/hyp.13446>
- Crockett, A. C., Ronayne, M. J., & Cooper, D. J. (2016). Relationships between vegetation type, peat hydraulic conductivity, and water table dynamics in mountain fens. *Ecohydrology*, 9(6), 1028–1038. <https://doi.org/10.1002/eco.1706>
- Crosbie, R. S., Binning, P., & Kalma, J. D. (2005). A time series approach to inferring groundwater recharge using the water table fluctuation method. *Water Resources Research*, 41(1), 1–9.
- Crosbie, R. S., Doble, R. C., Turndage, C., & Taylor, A. R. (2019). Constraining the Magnitude and Uncertainty of Specific Yield for Use in the Water Table Fluctuation Method of Estimating Recharge. *Water Resources Research*, 55(8), 7343–7361.
- Devito, K., Creed, I., Gan, T., Mendoza, C., Petrone, R., Silins, U., & Smerdon, B. (2005). A framework for broad-scale classification of hydrologic response units on the Boreal Plain: Is topography the last thing to consider? *Hydrological Processes*, 19(8), 1705–1714. <https://doi.org/10.1002/hyp.5881>
- Dettman, U. & Bechtold, M. (2016). Deriving Effective Soil Water Retention Characteristics from Shallow Water Table Fluctuations in Peatlands. *Vadose Zone Journal*, 15(10), 1–13.
- Dingman, S.L. (2015) *Physical Hydrology* (3<sup>rd</sup> ed.). Long Grove, IL: Waveland Press, Inc.
- Drexler, J. Z., Knifong, D., Tuil, J. L., Flint, L. E., & Flint, A. L. (2013). Fens as whole-ecosystem gauges of groundwater recharge under climate change. *Journal of Hydrology*, 481, 22–34. <https://doi.org/10.1016/j.jhydrol.2012.11.056>
- Duval, T. P. & Waddington, J. M. (2011). Extreme variability of water table dynamics in temperate calcareous fens: Implications for biodiversity. *Hydrological Processes*, 25(24), 3790–3802.
- Duval, T. P. & Waddington, J. M. (2018). Effect of hydrogeomorphic setting on calcareous fen hydrology. *Hydrological Processes*, 32(11), 1695–1708.
- ECCC. (2020). [https://climate.weather.gc.ca/historical\\_data/search\\_historic\\_data\\_e.html](https://climate.weather.gc.ca/historical_data/search_historic_data_e.html)

- Ferlatte, M., Quillet, A., Larocque, M., Cloutier, V., Pellerin, S., & Paniconi, C. (2015). Aquifer-peatland connectivity in southern Quebec (Canada). *Hydrological Processes*, 29(11), 2600–2612. <https://doi.org/10.1002/hyp.10390>
- Freeze, R. A. & Cherry, J. A. (1979). *Groundwater*. Englewood Cliffs, N.J.: Prentice-Hall, Inc.
- Gillham, R. W. (1984). The capillary fringe and its effect on water-table response. *Journal of Hydrology*, 67(1-4), 307-324.
- Goodbrand, A., Westbrook, C. J., & van der Kamp, G. (2018). Hydrological functions of a peatland in a Boreal Plains catchment. *Hydrological Processes*, 33(4), 562–574. <https://doi.org/10.1002/hyp.13343>
- Gribovszki, Z. (2018). Comparison of specific-yield estimates for calculating evapotranspiration from diurnal groundwater-level fluctuations. *Hydrogeology Journal*, 26(3), 869-880.
- Guan, X. J., Spence, C., & Westbrook, C. J. (2010). Shallow soil moisture – ground thaw interactions and controls – Part 2: Influences of water and energy fluxes. *Hydrology and Earth System Sciences*, 14(7), 1387-1400.
- Healey, R. W. & Cook, P. G. (2002). Using groundwater levels to estimate recharge. *Hydrogeology Journal*, 10(1), 91-109.
- Hill, A. J. & Durcholz, B. (2015). Specific Yield Functions for Estimating Evapotranspiration from Diurnal Surface Water Cycles. *Journal of the American Water Resources Association*, 51(1), 123-132.
- Hogan, J. (2006) Hydrologic behaviour and hydraulic properties of a patterned fen in Saskatchewan. University of Saskatchewan.
- Isabelle, P., Nadeau, D., Rousseau, A., Anctil, F. (2018). Water budget, performance of evapotranspiration formulations, and their impact on hydrological modeling of a small boreal peatland-dominated watershed. *Canadian Journal of Earth Sciences*, 55(2), 206-220.
- Janzen, K. & Westbrook, C. J. (2011). Hyporheic Flows Along a Channelled Peatland: Influence of Beaver Dams. *Canadian Water Resources Journal*, 36(4), 331-347.
- Karran, D. J., Westbrook, C. J., and Bedard-Haughn, A. (2018). Beaver-mediated water table dynamics in a Rocky Mountain fen. *Ecohydrology*, 11(2): e1923, 1-11. doi: 10.1002/eco.1923
- Keyantash, J. & National Center for Atmospheric Research Staff (Eds.) Last modified 07 Aug 2018. “The Climate Data Guide: Standardized Precipitation Index (SPI).” Retrieved from <https://climatedataguide.ucar.edu/climate-data/standardized-precipitation-index-spi>.
- Larocque, M., Ferlatte, M., Pellerin, S., Cloutier, V., Munger, J. L., Paniconi, C., & Quillet, A. (2016). Chemical and botanical indicators of groundwater inflow to Sphagnum-dominated

- peatlands. *Ecological Indicators*, 64, 142–151.  
<https://doi.org/10.1016/j.ecolind.2015.12.012>
- Liu, H. & Lennartz, B. (2019). Hydraulic properties of peat soils along a bulk density gradient – A meta study. *Hydrological Processes*, 33(1), 101–114.
- Lowry, C. S., Fratta, D., & Anderson, M. P. (2009). Ground penetrating radar and spring formation in a groundwater dominated peat wetland. *Journal of Hydrology*, 373(1–2), 68–79. Retrieved from <https://doi.org/10.1016/j.jhydrol.2009.04.023>Get rights and content
- Markovich, K. H., Manning, A. H., Condon, L. E., & McIntosh, J. C. (2019). Mountain-block Recharge: A Review of Current Understanding. *Water Resources Research*.  
<https://doi.org/10.1029/2019wr025676>
- Millar, D. J., Cooper, D. J., Dwire, K. A., Hubbard, R. M., & von Fischer, J. (2017). Mountain Peatlands Range from CO<sub>2</sub> Sinks at High Elevations to Sources at Low Elevations: Implications for a Changing Climate. *Ecosystems*, 20(2), 416–432.  
<https://doi.org/10.1007/s10021-016-0034-7>
- Millar, D. J., Cooper, D. J., & Ronayne, M. J. (2018). Groundwater dynamics in mountain peatlands with contrasting climate, vegetation, and hydrogeological setting. *Journal of Hydrology*, 561, 908–917. <https://doi.org/10.1016/j.jhydrol.2018.04.050>
- Moench, A. F. (1994). Specific Yield as Determined by Type-Curve Analysis of Aquifer-Test Data. *Groundwater*, 32(6), 949–957.
- Morrison, A., Westbrook, C. J., & Bedard-Haughn, A. (2015). Distribution of Canadian Rocky Mountain Wetlands Impacted by Beaver. *Wetlands*, 35(1), 95–104.  
<https://doi.org/10.1007/s13157-014-0595-1>
- National Wetlands Working Group. (1997). *The Canadian Wetland Classification System* (2<sup>nd</sup> e.d.). Warner, B. G. & Rubec C. D. A. (eds.), Wetlands Research Centre, University of Waterloo, Waterloo, ON, Canada.
- Nelson, M. L., Rhoades, C. C., & Dwire, K. A. (2011). Influence of Bedrock Geology on Water Chemistry of Slope Wetlands and Headwater Streams in the Southern Rocky Mountains. *Wetlands*, 31(2), 251–261.
- Price, J. S. (1992). Blanket bog in Newfoundland. Part 2. Hydrological Processes. *Journal of Hydrology*, 135(1–4), 103–119.
- Price, J. S. (1996). Hydrology and Microclimate of a Partly Restored Cutover Bog, Quebec. *Hydrological Processes*, 10(10), 1263–1272.
- Price, J. S. & Schlotzhauer, S. M. (1999). Importance of shrinkage and compression in determining water storage changes in peat: the case of a mined peatland. *Hydrological*

*Processes*, 13, 2591-2601.

- Quillet, A., Larocque, M., Pellerin, S., Cloutier, V., Ferlatte, M., Paniconi, C., & Bourgault, M. A. (2017). The role of hydrogeological setting in two Canadian peatlands investigated through 2D steady-state groundwater flow modelling. *Hydrological Sciences Journal*, 62(15), 2541–2557. <https://doi.org/10.1080/02626667.2017.1391387>
- Reed, M. S., Bonn, A., Evans, C., Glenk, K., & Hansjürgens, B. (2014). Assessing and valuing peatland ecosystem services for sustainable management. *Ecosystem Services*, 9, 1–4. <https://doi.org/10.1016/j.ecoser.2014.04.007>
- Rezanezhad, F., Price, J. S., Quinton, W. L., Lennartz, B., Milojevic, T., & Van Cappellen, P. (2016). Structure of peat soils and implications for water storage, flow and solute transport: A review update for geochemists. *Chemical Geology*, 429, 75–84. <https://doi.org/10.1016/j.chemgeo.2016.03.010>
- Roets, W., Xu, Y., Raitt, L., El-Kahloun, M., Meire, P., Calitz, F., ... Brendonck, L. (2008). Determining discharges from the Table Mountain Group (TMG) aquifer to wetlands in the Southern Cape, South Africa. *Hydrobiologia*, 607(1), 175–186. <https://doi.org/10.1007/s10750-008-9389-x>
- Sasaki, N., & Sugai, T. (2018). Holocene development of mountain wetlands within and outside of landslide in the Hachimantai volcanic group, northeastern Japan. *Quaternary International*, 471, 345-358.
- Seraphin, P., Goncalves, J., Vallet-Coulomb, C., & Champollion, C. (2018). Multi-approach assessment of the spatial distribution of the specific yield: application to the Crau plain aquifer, France. *Hydrogeology Journal*, 26(4), 1221-1238.
- Sophocleous, M. (1985). The Role of Specific Yield in Ground-Water Recharge Estimation: A Numerical Study. *Kansas Geological Survey*, The university of Kansas, Lawrence, Kansas.
- Spence, C., & Woo, M. (2006). Hydrology of subarctic Canadian Shield: Heterogeneous headwater basins. *Journal of Hydrology*, 317, 138–154. <https://doi.org/10.1016/j.jhydrol.2005.05.014>
- Streich, S. C., & Westbrook, C. J. (2020). The Hydrological Function of a Mountain Valley-Bottom Peatland Under Drought Conditions. *Hydrological Processes*, 34(2), 244-257.
- Thompson, Y., Sandefur, B. C., Miller, J. O., & Karathanasis, A. D. (2007). Hydrologic and edaphic characteristics of three mountain wetlands in Southeastern Kentucky, USA. *Wetlands*, 27(1), 174–188. [https://doi.org/10.1672/0277-5212\(2007\)27%5b174:HAECOT%5d2.0.CO;2](https://doi.org/10.1672/0277-5212(2007)27%5b174:HAECOT%5d2.0.CO;2)
- Toop, D.C. and N.N. de la Cruz, 2002. Hydrogeology of the Canmore Corridor and Northwestern Kananaskis Country, Alberta; Alberta Environment, Hydrogeology Section,

- Edmonton, Alberta; Report to Western Economic Partnership Agreement, Western Economic Diversification Canada.
- Valios, R., Schaffer, N., Figueroa, R., Maldonado, A., Yanez, E., Hevia, A., ... MacDonnel, S. (2020). Characterizing the Water Storage Capacity and Hydrological Role of Mountain Peatlands in the Aird Andes fo North-Central Chile. *Water*, 12(4).
- Viviroli, D., Archer, D. R., Buytaert, W., Fowler, H. J., Greenwood, G. B., Hamlet, A. F., ... Woods, R. (2011). Climate change and mountain water resources: Overview and recommendations for research, management and policy. *Hydrology and Earth System Sciences*, 15(2), 471–504. <https://doi.org/10.5194/hess-15-471-2011>
- Waddington, J. M., Quinton, W. L., Price, J. S., & Lafleur, P. M. (2009). Advances in Canadian Peatland Hydrology, 2003-2007. *Canadian Water Resources Journal*, 34(2), 139-148.
- Waddington, J. M., Morris, P. J., Kettridge, N., Granath, G., Thompson, D. K., & Moore, P. A. (2015). Hydrological feedbacks in northern peatlands. *Ecohydrology*, 8(1), 113–127. <https://doi.org/10.1002/eco.1493>
- Wang, S., Helgason, B., Westbrook, C., & Bedard-Haughn, A. (2016). Effect of mineral sediments on carbon mineralization, organic matter composition and microbial community dynamics in a mountain peatland. *Soil Biology & Biochemistry*, 103, 16-27.
- Westbrook C. J. & Noble B. F. (2013). Science requisites for cumulative effects assessment for wetlands. *Impact assessment and project appraisal*, 31(4), 318-323.
- Westbrook C. J. & Bedard-Haughn, A. (2016) Sibbald Research Wetland: Mountain peatland form and ecohydrologic function as influenced by beaver. *The Forestry Chronicle*, 92(1), 37-38.
- Westbrook C. J., Ronnquist, A., & Bedard-Haughn, A. (2020). Hydrological functioning of a beaver dam sequence and regional dam persistence during an extreme rainstorm. *Hydrological Processes*, 34(18), 3726-3737.
- White, W. N. (1932). Method of estimating groundwater supplies based on discharge by plants and evaporation from soil: results of investigations in Escalante Valley, Utah. In: *Geological Survey (U.S.) Water Supply Paper*, pp:105.
- Whitfield, P. H., van der Kamp, G., & St-Hilaire, A. (2009). Introduction to Peatlands Special Issue: Improving Hydrological Prediction in Canadian Peatlands. *Canadian Water Resources Journal*, 34(4), 303–310. <https://doi.org/10.4296/cwrj3404303>
- Whittington, P. N., & Price, J. S. (2006), The effects of water table draw-down (as a surrogate for climate change) on the hydrology of a fen peatland, Canada. *Hydrological Processes*, 20, 3589-3600.



- Winter, T. C. (1999). Relation of streams, lakes, and wetlands to groundwater flow systems. *Hydrogeology Journal*, 7(1), 28–45. <https://doi.org/10.1007/s100400050178>
- Winter, T. C. (2001). The Concept of Hydrologic Landscapes. *Journal of the American Water Resources Association*, 27(2), 355-349. DOI: 10.1111/j.1752-1688.2001.tb00973.x
- Wong, L. S, Hashim, R., & Ali, F. H. (2009). A review on hydraulic conductivity and compressibility of peat. *Journal of Applied Sciences*, 9(18), 3207-3218. DOI: 10.3923/jas.2009.3207.3218
- Xu, J., Morris, P. J., Liu, J., & Holden, J. (2018). PEATMAP: Refining estimates of global peatland distribution based on a meta-analysis. *CATENA*, 160(April 2017), 134–140. <https://doi.org/10.1016/j.catena.2017.09.010>
- Yu, Z., Loisel, J., Brosseau, D. P., Beilman, D. W., & Hunt, S. J. (2010). Global peatland dynamics since the Last Glacial Maximum. *Geophysical Research Letters*, 37(13), n/a-n/a. <https://doi.org/10.1029/2010GL043584>
- Zoltai, S. C., & Vitt, D. H. (1989). Holocene climatic change and the distribution of peatlands in western interior Canada. *Quaternary Research*, 33(2), 231–240. [https://doi.org/10.1016/0033-5894\(90\)90021-C](https://doi.org/10.1016/0033-5894(90)90021-C)

## APPENDIX A - R Script

R Script for extracting initial and peak water table depths following a rainfall event. Text in red indicates the code to be run. Lines with # in front of the text indicate comments and instructions as to how the code functions.

```
# Water table fluctuation extraction

#Load in CSV files, these need to be changed when using different datasets

well_data <- read.csv("FILENAME.csv")

rainfall_event_data <- read.csv("FILENAME")

#Convert time to POSIX Values

#Format Date/Time

well_data$Date.Time <- as.POSIXct(well_data$Date.Time, format = '%m/%d/%Y
%H:%M')

#Format Time for start of rainfall

rainfall_event_data$Start <- as.POSIXct(rainfall_event_data$Start, format =
'%d/%m/%Y %H:%M')

#Format Time for end of rainfall

rainfall_event_data$End <- as.POSIXct(rainfall_event_data$End, format = '%d/%m/%Y
%H:%M')

#Making date-time for the well data and rainfall data match – this step can be skipped if
needed.

#Matching time data for well and rainfall data

##the time conversion factor is a mathematical operation. E.g. 7*60min

rainfall_event_data$Start <- rainfall_event_data$Start – TIMECONVERSIONFACTOR

#Identify how long we want to look ahead in the well data following the start of the
rainfall event. E.g. (4 rows / hour) 4*24 = 24 hours after the rainfall event start. The
number of rows that equate to an hour in your dataset depend on the frequency of
measurements.

event_check_range <- 1*24

#Keep track of timeframes with missing data

na_counter <- 0

#Identify well data timestamps and rainfall timestamps for the period your examining.

##the timestamp name and well name will change with each dataset
```

```

well_timestamp <- "Date.Time"
well_data_name <- "Well_44.m"
rainfall_timestamp <- "Start"

#Declaration of output data frame

extracted_data <- data.frame("rise_start_timestamp", "rise_start_value",
"peak_timestamp", "Peak_value", stringsAsFactors = FALSE)
complete_extracted_data <- data.frame()
for(rainfall_index in 1:nrow(rainfall_event_data)){

#Find the start and end index in the well data for which the rainfall event corresponds
rainfall_event_start <- rainfall_event_data[rainfall_index, rainfall_timestamp]

start_index <- which (well_data[[well_timestamp]] == rainfall_event_start)
end_index <- start_index + event_check_range

for (well_data_index in start_index:end_index){

  previous_well_data <- well_data[well_data_index - 1, well_data_name]

  current_well_data <- well_data[well_data_index, well_data_name]

  next_well_data <- well_data[well_data_index + 1, well_data_name]

  if(is.na(current_well_data)){

    na_counter <- na_counter + 1

  }

#Checks for Data discrepancies

valid_value_check <- is.na(previous_well_data) || is.na(current_well_data) ||
is.na(next_well_data)

#THIS SECTION CHECKS FOR PEAKS – this is done by scanning forward in the well
data after the start of the rainfall event to find the highest value within a given time frame

print(peak_value)

if((!valid_value_check) &&

  (current_well_data > previous_well_data) &&

  (current_well_data > next_well_data) &&

  (current_well_data >= peak_value)){

  peak_value <- current_well_data

```

```

    peak_timestamp <- well_data[well_data_index, well_timestamp]
  }
}

if( na_counter != event_check_range)

#THIS SECTION CHECKS FOR TROUGHS – this is done by scanning backwards from
the identified peak water table value and locating the smallest water table after the start of
the rainfall event

trough_start_index <- which(well_data[[well_timestamp]] == peak_timestamp)

fudge_factor <- 0.005

trough_value <- peak_value

for (trough_index in trough_start_index:start_index){

  previous_well_data <- well_data[trough_index + 1, well_data_name]
  current_well_data <- well_data[trough_index, well_data_name]
  next_well_data <- well_data[trough_index - 1, well_data_name]

  if(!is.na(current_well_data)){

    if((current_well_data < previous_well_data) &&
      (current_well_data < next_well_data)){

      trough_value <- current_well_data

      trough_timestamp <- well_data[trough_index, well_timestamp]

      extraced_data <- rbind(extraced_data, c(as.character(trough_timestamp), trough_value,
as.character(peak_timestamp), peak_value))

      break
    }
  }
}

}

print(extraced_data)

```

## APPENDIX B - Specific yield for Sibbald Fen

Well	Minimum	Maximum	Range	Median
3	0.04	0.82	0.78	0.18
4	0.02	0.61	0.59	0.10
7	0.03	0.50	0.47	0.18
11	0.02	0.08	0.06	0.07
14	0.11	0.88	0.77	0.19
15	0.05	0.49	0.44	0.12
19	0.10	0.88	0.78	0.39
20	0.08	0.55	0.47	0.19
23	0.07	0.63	0.56	0.19
27	0.02	0.56	0.54	0.12
30	0.10	0.45	0.35	0.27
38	0.03	0.26	0.23	0.11
44	0.00	0.85	0.85	0.28
49	0.03	0.67	0.64	0.16
60A	0.02	0.46	0.44	0.05
60B	0.03	0.66	0.63	0.07
61	0.03	0.28	0.26	0.11
62	0.02	0.73	0.71	0.28

Table B.1 Range of  $S_y$  values found for each well studied at Sibbald Fen.

## APPENDIX C - Plot of water table depths by well

